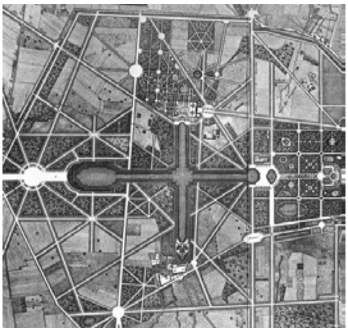
Space and Price in Adapting Cities –

Exploring the Spatial Economic Role of Climate-Sensitive Ecological Risks and Amenities in Finnish Housing Markets

Athanasios Votsis



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Title

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Abstract

As the adaptation of cities to climate change is increasingly overlapping sustainable urban development, the necessity to harmonize climate-proofing with economic objectives becomes ever clearer. Climate-sensitive ecological risks and amenities, and their role in markets and urban planning, are central in this issue.

This research explores the reaction of urban housing markets to changes related to green amenities and flood risks; deepens the understanding of complex spatial processes, in housing markets and urban growth, that relate to the implementation of sustainable adaptation strategies; and develops advanced spatial modelling methodology that renders urban economic analysis better suitable to address questions of sustainable and climate-proof urban planning. The results demonstrate that physical or behavioral planning interventions surrounding climate-sensitive ecological risks and amenities generate economic benefits via multiple channels, when attuned with market mechanisms. This is an important building block in synchronizing climate-proofing with economic development objectives, therefore facilitating urban adaptation that is also sustainable. The synchronization requires an evidence-based understanding of the effects linked to particular interventions, at concrete locations and spatiotemporal scales. The overall message is that, while trade-offs are unavoidable, if green cities maintain agglomeration benefits, ensure increased information flows about ecological risks and amenities, while implementing amenities in a spatially parameterized manner, they are able to achieve both climate-proofing and sustainability objectives.

The thesis consists of five quantitative analysis articles, while the introductory chapter synthesizes the results in the context of urban planning, spatial economics, and climate change adaptation. The first three articles apply empirical microeconometric methodologies (spatial hedonic and difference-in-differences analysis) to explore the response of housing markets to changes in green infrastructure and to policy instruments related to flood risk information. The fourth and fifth articles apply spatial complexity methods (cellular automata, fractal geometry) to extend the intuitions of microeconometric estimations into dynamic spatial processes in housing prices and urban growth. The five articles use environmental-economic datasets developed by this dissertation research, covering the urban region of Helsinki (Helsinki, Espoo, and Vantaa) and the cities of Pori and Rovaniemi.

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Contemplating these essential landscapes, Kublai reflected on the invisible order that sustains cities, on the rules that decreed how they rise, take shape and prosper, adapting themselves to the seasons, and then how they sadden and fall in ruins. At times he thought he was on the verge of discovering a coherent, harmonious system underlying the infinite deformities and discords, but no model could stand up to the comparison with the game of chess.

[…]

“I have also thought of a model city from which I deduce all the others,” Marco answered. “It is a city made only of exceptions, exclusions, incongruities, contradictions. If such a city is the most improbable, by reducing the number of abnormal elements, we increase the probability that the city really exists. … But I cannot force my operation beyond a certain limit: I would achieve cities too probable to be real.”

Italo Calvino, *Invisible Cities*

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I dedicate this work to Dina, Marianna, and Christiana; to Anastasia, John V, and John K; and to Adriaan. This is an important milestone, and I will always remember your belief in me.

Athanasios Votsis
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Allocation of work: Articles I-II and IV-V are the work of the author alone. In article III A. Votsis is responsible for approximately 80% of the work, including all of the data set assembly, the majority of literature review, most of the econometric and spatial analysis, the majority of the writing, and most of the revisions and final editing of the manuscript.

Introduction and Synthesis

1. Overview

For cities of the 21st century, successful adaptation to the changing climate entails the planning of sustainable urban areas; conversely, successful urban planning entails the climate-proofing of urban areas. The topic of this dissertation is the role of climate-sensitive ecological risks and amenities in sustainable urban planning and the adaptation of cities to climate change. Risks are studied through urban flooding, while amenities through natural urban land uses. The research focuses on spatial economic mechanisms and processes active at the intersection of real estate markets and land use planning. The aims are to: (1) explore the reaction of housing markets to changes related to green amenities and flood risks; (2) deepen the understanding of complex spatial processes, in housing markets and urban growth, that relate to the implementation of sustainable adaptation strategies, and (3) develop advanced spatial modelling methodology that renders urban economic analysis better suitable to address questions of sustainable and climate-proof urban planning.

The significance of this dissertation consists in identifying empirical links between climate-proofing and economic sustainability tasks in the context of spatial planning, in delineating ways for their synchronization, and in integrating urban economic and spatial analysis methodologies. The results demonstrate that physical or behavioral planning interventions surrounding climate-sensitive ecological risks and amenities generate economic benefits via multiple channels, when attuned with market mechanisms. This is an important building block in synchronizing climate-proofing with economic development objectives, therefore facilitating urban adaptation that is also sustainable. The synchronization requires an evidence-based understanding of the effects linked to particular interventions, at concrete locations and spatiotemporal scales. Moreover, the results communicate the necessity to coordinate multiple temporal and spatial scales in the planning of amenities and risks; both in research and decision-making. The key implication of this dissertation is that, while trade-offs are unavoidable, if green cities maintain agglomeration benefits, ensure increased information flows about ecological risks and amenities, and implement amenities in a spatially parameterized manner, they are able to achieve both climate-proofing and sustainability objectives.

The dissertation responds to the need for connecting sustainable urban planning with urban adaptation. These two fields are increasingly overlapping, mainly via their interest in the management of climate-sensitive risks and amenities. The general research problem to which this dissertation contributes is how to conceptualize and plan cities that are able to adapt in a sustainable way (economically, socially, and environmentally) to the impacts of climate change. Solving this problem represents a challenge, as it involves environmental and socioeconomic processes at more than one spatial scale; it has short- and long-term aspects; and it requires the harmonization of a diverse—and often conflicting—array of objectives. Moreover, solutions to the problem must take into account top-down and bottom-up responses, as well as combine physical and behavioral planning interventions. Taking into consideration these challenges, the research focuses on two major socioeconomic aspects of climate-proofing methods: first, it tracks the response of urban residential real estate prices to climate-sensitive ecological risks and amenities as an important indicator of the economic viability of climate-proofing methods; second, it uses the modelling and simulation of the spatial evolution of built environmental morphology and of house prices as a tool that enables the assessment of the impacts of alternative adaptation interventions on the entire city.

The dissertation has two overarching research questions. The first is: how does the spatial distribution of ecological risks and amenities influence the formation and differentiation of residential real estate value? The question is explored with economic and geospatial microdata from Helsinki's urban region (the municipalities of Helsinki, Espoo, and Vantaa) and the cities of Pori and Rovaniemi. The principal approach is hedonic pricing, implemented via spatial econometric models. Data on sea and river flooding are utilized to explore the risk dimension, while terrestrial (urban green) and aquatic (urban blue) natural land uses are employed to explore the amenity dimension. The second overarching research question is: how do the above price effects relate to the spatial organization of the built environment? This question is explored with data from Helsinki's urban region. Spatial modelling and simulation are the principle approaches; they complement the econometric estimations and provide information about dynamical spatial processes of a more comprehensive character related to land use change, urban growth, and real estate value behavior.

Methodologically, the research relies on econometrics and advanced spatial analysis methods. It adopts a rational (as opposed to aesthetical) planning perspective, using tools and theories of urban and regional planning, urban economics, and quantitative human geography. As urban planning is an architectonic discipline, climate-sensitive risks and amenities are approached in relation to concrete natural and manmade elements of the built environment. The links of spatial elements, risks, and amenities to economic phenomena and dynamical urban development processes enables one to understand that it is not the mere presence, but the role of risks and amenities in urban economic mechanisms, that influences urban adaptive capacity.

The dissertation's research questions are addressed in five articles. It should be stressed that the articles, although stand-alone studies, should not be taken separately; they divide the dissertation's tasks and are arranged in a structure that exposes increasingly complex spatial mechanisms surrounding the treated topics. The thesis starts with articles I-III, which demonstrate what can be done on the topic of housing markets and ecological risks and amenities when econometric methodologies (hedonic analysis; difference-in-differences analysis) are applied on high quality economic-environmental microdata. Consequently, the first three articles offer a comparison to other works in the field and serve as benchmarks in how sustainable and climate-proof goals can be assisted by housing market analysis. The thesis continues with articles IV-V, which demonstrate the limitations of econometric methodologies and show how their results can be deepened and supplemented by the means of alterative spatial modelling and simulation methodologies (fractal geometry; cellular automata). The final two articles also demonstrate the necessity of expanding the analytical scope from housing markets into wider urban spatiotemporal processes and mechanisms.

Article I, "Ecosystems and the spatial morphology of urban residential property value: a multi-scale examination in Finland," (available as a working paper) prepared georeferenced hedonic datasets and hedonic models—refined in articles II and III—that were not previously available in Finland for addressing questions of climate-proof sustainable urban planning. It is a foundational analysis of the role of ecological amenities in the formation and differentiation of house prices in Finnish housing markets at various spatial scales. Having done this, the study focuses on the scale of individual properties and assesses in further detail the spatial behavior of the marginal prices of amenities. Various time-periods are also tested for assessing the temporal sensitivity of the explored effects.

Article II, "Planning for green infrastructure: the spatial effects of parks, forests, and fields on Helsinki's apartment prices," (published in *Ecological Economics*) estimates, from an implementation viewpoint, the spatial spillover effects of urban green on housing prices in Helsinki's urban region. The marginal values of parks, forests, and grass fields are estimated as functions of distance to the city center, and their pure and spatial spillover components are separated. The paper discusses conditions under which urban green capitalizes positively in house prices and the manner in which the capitalization effects spillover to and from neighboring locations. The article then provides recommendations about the planning of green infrastructure.

Article III, "Housing prices and the public disclosure of flood risk: a difference-in-differences analysis in Finland," (published in the *Journal of Real Estate Finance and Economics*) turns to the risks of ecosystems and explores the effects of imperfect information about coastal flood risks. The study focuses on Helsinki-Espoo, Pori, and Rovaniemi and identifies price adjustments in their coastal housing markets induced by the public disclosure of official high-resolution flood risk maps. The article also estimates the sensitivity of the price adjustments to flooding probability in Helsinki-Espoo, the connection of these adjustments to bounded-rational behavior of the housing market towards risk levels, and the correspondence of these adjustments to flood damage cost functions.

Article IV, "Utilizing the SLEUTH cellular automaton model to explore the influence of flood risk adaptation strategies on Greater Helsinki's urbanization patterns," (in revision with *Computers, Environment, and Urban Systems*) connects the estimations of article III to spatial simulation, focusing on flood risk management and urbanization. A cellular automaton urban growth model is calibrated and run for the Greater Helsinki region. The model is used to simulate the impact (until 2040) of alternative spatial strategies inside flood risk zones on annual urbanization parameters in and beyond their application areas. The tested scenarios compare market- and regulation-led growth constraints to current urbanization trajectories.

Article V, "Exploring the spatiotemporal behavior of Helsinki's housing prices with fractal geometry and co-integration," (forthcoming in the *Journal of Geographical Systems*) examines the topic of temporal equilibria and disequilibria in the spatial morphology of quarterly house prices at multiple spatial scales in Greater Helsinki during 1977–2011. Fractal geometry is used to quantify the spatial morphology of price/m^2 clusters across a spectrum of spatial scales, simultaneously. Time series at two indicative spatial scales (city-wide and neighborhood) are produced and analyzed with vector error correction models that explore the in- and out-of-equilibrium interplay between the fractal geometries of high and low price/m^2 areas at each scale.

2. A new challenge for urban research: Linking adaptation and sustainable urban planning

As urban adaptation responds to climate change impacts at the urban scale, it meets the long history of urban planning. At the same time, while urban planning has been historically concerned with environmental issues, climate-specific challenges represent something new for this field. As a result, the two approaches should not be seen as competing, but rather as complementary. There is a need, in other words, to highlight linkages between these two fields, and show what they can learn from each other. In the 21st century, there are new terms of thinking about cities. Urban adaptation to the impacts of climate change entails the planning of sustainable urban areas. Conversely, urban planning entails the climate-proofing of cities. This Section places the dissertation in the context of the interplay between urban adaptation and urbanism.

Adaptation to the impacts of climate change on nature and humankind (i.e. the consequences of climate change) is one of the three fundamental divisions of climate change research as stated by the Intergovernmental Panel on Climate Change (IPCC), along with research in the natural science of the climate system, and in the mitigation of climate change, notably the reduction of greenhouse gas emissions (causation of climate change). Adaptation and urbanism, their overlap being the context of this research, are linked through sustainable development and their interactions in industries, human settlements, and society (Wilbanks et al. 2007; Wheeler 2011; Calthorpe 2013). Central in this link are climate-sensitive ecological risks and amenities. Risks are understood as climate and weather -related threats, e.g. floods. Anthropogenic climate change, overlaid on the natural variability of the climate, results in the heightening of the intensity and/or change of familiar (for urban management and planning) spatiotemporal patterns of weather events. Amenities are beneficial aspects of the natural environment, e.g. the capacity of green spaces to reduce the impact of floods. One of the central tasks in the climate-proofing of cities and markets through spatial policy and planning is finding new ways to manage risks and amenities, first in connection to each other, and then in connection to spatial economic mechanisms upon which a city relies.

Urban adaptation refers to physical and social modifications of cities as means for better coping with climate-related impacts. The impacts are regionally variable, depending on geographical, social, and sectoral contexts (Wilbanks et al. 2007). More specifically, the risk of climate-related impacts is a function of the intensity of a hazard, the exposure to the hazard, and the socioeconomic vulnerability of the exposed population (IPCC 2012; IPCC 2014). The current (5th) assessment report of the IPCC identifies flooding, water shortages, and extreme heat stress as the key risks of climate change for the European continent (IPCC 2014). In application to human settlements, the 4th assessment identifies extreme weather events as the major threat (Wilbanks et al. 2007), while the 5th assessment identifies flooding, temperature variation, drought and water scarcity, and human health and epidemiology issues as key risks in urban areas (Revi et al. 2014). Coastal and river-line areas, as well as areas with economies linked to climate-sensitive resources such as agriculture, forestry, and tourism are identified as the most vulnerable locations (Wilbanks et al. 2007).

At the same time, it is recognized that the adaptive capacity of settlements, industry, and society is considerable, depending on the financial and organizational resources of individuals, communities, sectors, and governments (Wilbanks et al. 2007; Barnett et al. 2015). Actions to address climate risks relate in more than one instances to urban planning, notably spatial planning, land use planning, and urban policy. Urbanization, population, and economic trajectories are the underlying context, while multiscale spatial and temporal processes, and the key role of green infrastructure and housing are explicitly mentioned as important elements (IPCC 2014; Revi et al. 2014). Green infrastructure is a key element in managing the risks of extreme weather events (Givoni 1991, 1998; European Commission 1994, 2011, 2013; European Environment Agency 2011; IPCC 2012;

Renaud et al. 2013). The concept of green infrastructure refers to a systematic view of a city's natural spaces, the planning of which has far-reaching effects, similar to the case of planning technical infrastructure. Spatial planning is also a tool that connects adaptation and mitigation, as the density and spatial organization of the built environment, land use composition and use of green infrastructure, energy footprint, and connectivity and accessibility determine the emission footprint of urban areas (Seto et al. 2014). The way urban adaptation is understood by the IPCC is directly connected to notions of comprehensive and sustainable urban planning. This link is acknowledged in the 4th assessment and further elaborated in the 5th assessment, which explains that adaptation does not only concern risks, but also represents opportunities for cities: those cities that, in view of climate change impacts, have addressed weak points in their natural, technical, and socioeconomic components (Revi et al. 2014) gain a comparative advantage.

While urban adaptation comes to recognize its links to sustainable urban planning, urbanism (thinking about and planning cities – see Hall 2002; LeGates and Stout 2011) has for a long time been occupied with intertwined environmental and socioeconomic concerns. The archeological record contains environmental considerations in site location and grid planning (Ward-Perkins 1996; Düring 2006, 2011; Schmidt 2010; Soja 2010; Dietrich et al. 2012; Thommen 2012; Hughes 2014), whereas the treatise of Roman architect Vitruvius relates site location to local environmental conditions and street grid design to prevailing winds (Book 1, Chapters IV, VI). In the 19th century, environment and economics became ever more interlocked in urban planning. The form, scale, and location of natural spaces was central in visions about social structure and interaction, mobility, and the organization of activities. Early examples were reactions to health and social challenges in industrial cities and their slums (Hall 2002; Bass Warner 2011). Ebenezer Howard's Garden City was an alternative to industrial cityscapes and represents a deliberate linking of green space to spatial economic organization and social theory. Le Corbusier's Ville Radieuse and Frank Lloyd Wright's Broadacre City are plans of, respectively, dense and scattered settlements and represent sharply contrasting visions about land use and social structure. Meanwhile, the monumental urban design movement was the first to emphasize green aesthetics (Hall 2002; Fishman 2003).

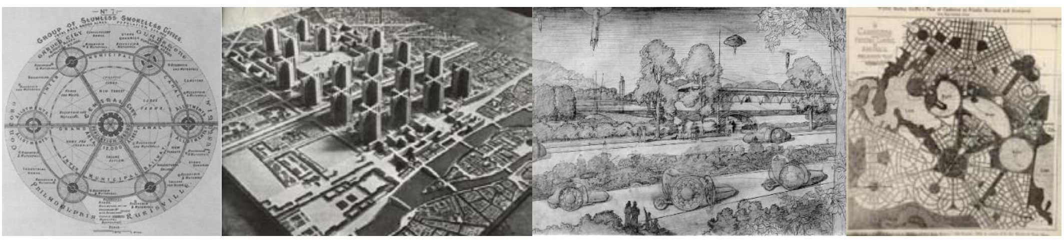


Figure 1 (left to right): Howard's Garden City, Le Corbusier's Ville Radieuse, Lloyd Write's Broadacre City, and Griffin's monumental plan of Canberra.

Since the 1990's the paradigm of sustainable development has had a formative influence in the consideration of ecological and socioeconomic objectives in relation to each other and within a unified strategic framework. Sustainable development is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987, Chapter 2). In practice, this objective has been linked to balancing three dimensions: economic development, social wellbeing and equity, sound condition and functioning of the natural environment. The commission's message resonated well with the scope and problems that occupy urban planning and, unlike other theories, sustainable development has impacted everyday planning and architectural practice. For instance, the LEED standards and ratings by the U.S. Green Building Council and the EarthCraft design standards are operational applications of sustainability principles in construction, site design, and real estate development. Similarly, the theory of new urbanism proposes the implementation of compact built forms, mixed land uses, green infrastructure, and human-scaled urban layout and infrastructure, as well as the re-prioritization of urban public space and socioeconomic diversity as solutions for climate change mitigation and adaptation (van der Ryn and Calthorpe 2008; Calthorpe 2013). At the same time, due to the lack of empirical information, the multiplicity of objectives contained in sustainable urban planning has raised debates on optimizing conflicting objectives and prioritizing costs and benefits (Campbell 1996; Verhoef and Nijkamp 2002; Brooks et al. 2012).

Despite the sparse links in urban research between environmental, socioeconomic, and climate-proofing solutions, the empirical connections of sustainable urban planning to climate change adaptation have not yet been sufficiently researched. Knowledge on climate-proof and sustainable cities is currently rather conceptual and lacks evidence-based concretization and empirical analysis. In response, this thesis focuses on the effects of physical and behavioral planning interventions involving natural land uses and the risks and amenities attached to them; such interventions should facilitate both climate-proof and sustainability objectives.

The dissertation research is focused primarily on understanding the effects of flood risk information and natural amenities in the prices of urban dwellings, as well as on understanding the role of urban growth processes related to land use and house prices in adaptation. On one hand, the estimated price effects are used to identify best land use configuration practices, which ensure that the implementation of green infrastructure—a recommended adaptation action by the IPCC—aligns also with local economic development objectives. On the other hand, the price effects are used to identify weak elements in housing markets concerning flood risks and to assess the effectiveness of information policies as part of adaptation strategy. Price effects of flood risk information are also translated to alternative growth management strategies, which helps understand the relation between adaptation strategy and long-term urbanization behavior. Lastly, a more theoretical endeavor is the exploration of multiple spatial and temporal scales in the geographical configuration of housing prices. Both of the last two elements relate to IPCC's recommendation for exploring multiple spatial and temporal scales and for understanding the urbanization background of urban adaptation.

3. Past studies on risks and amenities in the housing market and urban planning

This Section reviews key literature on the subject; selected minor sources can be found throughout this Chapter. More extensive literature on specific topics can be found in the individual articles. The theoretical basis of the dissertation is discussed in Section 4.

The effects of ecological risks and amenities on urban housing markets have been studied extensively, mainly through the capitalization of risky or beneficial natural features in property prices. The amenity value of urban green is measured by the majority of studies either by estimating marginal changes in the price of properties as their proximity to a green patch changes, or via price premiums in properties within a certain radius from green patches in relation to those farther away. The meta-analyses of Brander and Koetse (2011), Perino et al. (2014), and Siriwardena et al. (2016) provide thorough up-to-date summaries of the effects of green spaces on housing prices. The researchers specify the following main parameters of these effects: proximity to green spaces increases property prices; this effect fades out when moving away from green spaces; and housing markets appear to be selective about the type and size of green spaces regarded as desirable. In Finland, Tyrväinen (1997) and Tyrväinen and Miettinen (2000) report similar results on all three parameters. Other sources relate the price effect of urban green to scarcity (Siriwardena et al. 2016) or scarcity-crowdedness (Brander and Koetse 2011) arguments. It is observed that the capitalization of urban green on dwelling prices is generally higher as urban green becomes scarcer, as the built environment becomes denser, and as its preservation chances increase. While the benefits of urban green have been divided into detailed categories—the U.K. National Ecosystem Assessment is a major paradigm (Davies et al. 2011; see also Section 4 on ecosystem services)—the positive effect of urban green on property prices is typically estimated either as a generic amenity effect or a more specific scenic effect. This lack of detail is supported by the study of Czembrowski and Kronemberg (2016), who find that housing markets are not able to distinguish fine or singular items of green benefits, but see urban green more abstractly (albeit with certain conditions on size and type). The studies of Wolch et al. (2014) and Perino et al. (2014) raise attention to the correct implementation of urban green. According to them, studies of valuation of green amenities imply that, while urban green has the potential to increase property prices, its incorrect placement has the capacity to destroy millions worth of economic value.

At the same time, studies detect a negative response of the housing market for properties in the presence of occurred or potential natural hazard risks (Kiel and McClain 1995; McCluskey 1998; McCluskey and Rrausser 2000; Pope 2008a, 2008b). Specifically for flooding, Daniel et al. (2009) provide a meta-analysis on the effects of flood risk in the housing market, noting that, while flood risk clearly affects housing prices negatively, the key issue is to be able to separate the concurrent amenity and risk dimensions of the coast. Indeed, price premiums are widely reported in relation to the coast (e.g. Leggett and Bockstael 2000; Conroy and Milosch 2011), while examples of concurrent estimation of price premiums and discounts related to coastal locations are Bin et al. (2008a, 2008b). However (as discussed in more detail in Section 4), the price discount of flood-prone properties does not always accurately reflect the actual risk level, as information gaps and asymmetries are a known imperfection of the housing market (Pope 2006). The behavioral source of this phenomenon is accounted for by research on bounded rationality and biased risk perception (Kahneman and Tversky 1979; Tversky and Kahneman 1986). Furthermore, studies report that past floods are often forgotten (Atreya et al. 2013; Bin and Landry 2013). Filatova and Bin (2013) showed that risk perception in the housing market can also evolve to adapt to changing flood risks, which in turn influences the underlying mechanisms of land and property price formation.

The abovementioned sources study primarily direct short-term effects within the borders of the housing market. At the same time, literature on adaptation has been increasingly pointing out that there is a need for a deeper and broader analysis—i.e. in connection to multiple urban functions and economic sectors—of risks and adaptation options. The IPCC literature mentioned in Section 2 provides the strategic framework, whereas Meyer et al. (2013) talk specifically about extreme events and Aerts et al. (2014) are concerned with urban flooding. In response to the need for comprehensive assessments of adaptation options, studies increasingly look at more than one segments of the urban or regional economy in order to assess direct and indirect impacts and optimal policy responses with more than one sector and objective in mind. Hallegatte (2008, 2014) developed a regional input-output model to study the impacts of extreme weather events on a region's economy, while the EU FP7 project ToPDAd (Tool-supported policy development for regional adaptation) was among the first studies to employ a cluster of sectoral and multi-sectoral models in order to explore the impacts of alternative adaptation options on regional economies for various climate, socioeconomic, and adaptive behavior scenarios (Aaheim et al. 2015; Perrels et al. 2015). In Finland, Perrels et al. (2010) assessed the direct and indirect economic impacts of flooding events for different hydrological parameters and various economic sectors. At the sub-regional level, spatially disaggregated equilibrium-based microeconomic models that were in the past used in economic development and transport investment assessments are now increasingly applied in the environmental domain. They model the co-evolution of land use, infrastructure, and economic activity through interactions and flows within and between multiple sectors and markets (Anas 1987, 2013; Wegener 1994; Echenique et al. 2013; Jin et al. 2013). A more recent set of approaches employs agent or cell -based microsimulation models to understand processes at very fine levels of spatial detail (Waddell 2002; Kim and Batty 2011). Examples of applications of microsimulation models in sustainable development and climate adaptation topics are Houet et al. (2016), who focus on joint urban climate – urban growth modelling, and Jantz et al. (2010), who assess sustainable urban/regional growth strategies. Lastly, Chrysoulakis et al. (2013, 2014), drawing from the growing capacity of urban sciences to link models of biophysical and socioeconomic processes, discuss the urban metabolism approach, i.e. the integrated modelling of the complete set of biophysical and socioeconomic flows and processes of an urban system.

4. Theoretical basis: Urban economic theory and alternative approaches

This Section discusses urban residential location, land use, and housing price formation and differentiation. These aspects of the urban economy provide the context for adaptation strategy in the housing market but also in wider-scoped spatial planning, because they address the issue of why cities emerge and evolve as they do. Urban complexity theory is then introduced as an alternative spatial modelling and simulation approach. Urban complexity provides an integrative framework to model and understand the wider links between housing prices, urban growth processes, and ecological risks and amenities.

4.1. The Alonso-Muth-Mills model

The Alonso-Muth-Mills (AMM) model is a widely accepted urban economic model that describes why cities emerge and grow as they do. The main implication of the AMM model in connection with adaptation strategy is that the task of climate-proofing a city is not a purely environmental or a purely straightforward objective. This objective is in fact intertwined with how cities grow and function; it is further complicated by the fact that the growth of cities generates wealth—i.e. reduces socioeconomic vulnerability—and, at the same time, exposes cities to ecological threats. Urban adaptation is called to enhance, but not completely disrupt beneficial urban mechanisms, since environmental and socioeconomic objectives are both elements of successful climate adaptation.

The AMM model describes the growth of cities based on the spatial interaction of firms and households. Its point of departure is the concepts of economies of scale and economies of agglomeration. Economies of scale describe that as firms grow, the more efficient they become in per unit and diversity of output, while economies of agglomeration describe that, by clustering in space, firms benefit from a tight network of inputs, outputs, services, infrastructure, and labor (Brueckner 2011). The particular geographical location in which agglomeration and scale processes will succeed owes to randomness, historical accident, physical determinism, natural advantage, and comparative advantage (O'Sullivan 2000; Batty 2007). The combination of situational factors with agglomeration and scale economies typically results in a market area and, as the original benefits facilitate additional growth, in urban agglomerations and cities. Local environmental conditions drive or participate in several of those processes; examples are the emergence of mining towns (natural resources), port cities (access to sea routes), and hilltop cities (topographic advantage).

However, natural land uses change substantially as urban growth occurs. Using household income, commuting cost, distance to the city center (or central business district – CBD), land rent, housing prices, and dwelling size, the main implications of the AMM model can be summarized as follows (O'Sullivan 2000; Brueckner 2011):

[1] As distance to the CBD increases, commuting costs rise, whereas households and firms are characterized by spatially uniform utility and profit.
[2] Point [1] implies that land rent and, consequently, building heights decrease as distance from the CBD increases.
[3] Point [1] also implies that as distance to the CBD increases, housing price per square unit decreases, and consequently the size of dwellings increases.
[4] Points [2]-[3] imply that the density of urban development decreases as distance to the CBD increases. In the CBD, high land rent and property prices per square unit drive land to be used in ever-decreasing fractions.
[5] Adding commercial and agricultural firms—and considering further elements of bid-rent theory—implies that commercial land use will dominate the CBD, residential land use will be typically found near the center, while agricultural land use is found in the urban periphery.

Points [1]-[5] describe the land use of a monocentric city. Adding two household income groups, introducing three types of spatially variable amenities (natural, historical, and cultural), and assuming a positive valuation of amenities (Brueckner et al. 1999; Brueckner 2011) result in:

[6] High-income households locating near exogenous ecological and historical amenities.
[7] Cultural amenities (e.g. cafés, art districts) endogenously appearing in high concentrations of high-income households, which in turn attracts further investment and high-income residents.
[8] Decentralized employment hubs and a spatially heterogeneous transport infrastructure will further disrupt the spatially uniform utility of households.

[9] Points [6]-[8] yield a multicentric city in which the geographical distribution and variation of local environmental conditions are both a driver and result of wider spatial processes.

In this dissertation the AMM is used to explain why the spatial equilibrium of dense urban agglomerations is more productive than fundamentally different spatial configurations (Glaeser and Gottlieb 2009). This implies that climate-proofing tasks and spatial economic mechanisms need to be linked in order to ensure benefits in both sides and to identify optimal urban adaptation strategies. Practically, this often has to do with identifying optimal targets about density, allocation of space to green infrastructure, land use configuration, and urban design.

The AMM model also offers a starting point for approaching the spatial morphology of ecosystems as amenities and climate-related hazards as risks. More specifically, competition of households and firms to locate in the central areas of an agglomeration results in the minimization or expulsion of less competitive land uses, including natural land uses (points [2]-[4] above). The concepts of risks and amenities become relevant because the absence or minimization of ecosystems in central urban areas means a loss or reduction of the capacity for regulating local climate, hazards, noise, and the quality of water, soil, and air (through regulating urban ecosystem services), and a worsening of fundamental health and socioecological aspects (through cultural and provisioning urban ecosystem services) (Davies et al. 2011; Niemela 2012). Thus, the beneficial aspects of urban ecosystems are seen in residential location dynamics and housing price formation as desirable, i.e. as amenities. Conversely, hazards are seen as disamenities or risks. Ecological risks and amenities are linked, since the presence of green amenities may—depending on the case—reduce ecological risks (e.g. the use of green spaces may be used to regulate heat stress), or coincide with risks (e.g. double character of the coastline that provide scenic amenities *and* generate floods).

4.2. Hedonic theory of house prices; risks and amenities as hedonic attributes

While the AMM model describes the overall mechanism of house price formation, hedonic price theory focuses on detailed factors of price differentiation. Hedonic theory is a widely used methodology for assessing the costs and benefits of ecological risks and amenities in the housing market. It should be noted that, although cities contain other types of real estate, this dissertation has focused primarily on residential real estate (used interchangeably with the terms "housing" or "dwellings"). From the viewpoint of urban adaptation policy, housing is a special good. First and foremost, it is linked to primary habitation notions such as shelter, safety, and family. Even so, in urban areas, housing is: notably expensive, worth several times a typical household's annual income; its buying or selling requires significant time and information resources; it plays a central role in the lives of individuals and families (Euchner and McGovern 2003). Moreover, housing is heterogeneous (it varies in such features as size, age, and location), immobile, involves high moving costs, and the housing market is subject to socioeconomic segregation and discrimination (O'Sullivan 2000). These features make housing a focal point in adaptation and resilience strategy; as IPCC (2014) notes, and with special reference to economically vulnerable households, a well-functioning market with respect to risks can absorb much of climate-related impacts. The housing market is thus an important indicator in assessing the adaptive capacity of urban areas.

For households, the implication of the AMM model in connection to ecological amenities and risks is, among others, a spatially heterogeneous distribution of locational benefits and disadvantages. Since not everyone can locate at the "best" place, households that are outbid by wealthier ones will locate at less than optimal areas. In the housing market, when a match between seller and buyer occurs, the agreed price will compensate for locational (dis)advantages (DiPasquale and Wheaton 1996). Hedonic price theory, first described by Rosen (1974), is widely used to derive the monetary value of marginal changes in risks and amenities (Tyrväinen 1997). Ecological risks and amenities have been increasingly approached as hedonic attributes in order to derive the willingness to pay for amenities or willingness to avoid risks, as well as to estimate the economic value of marginal changes in risks and amenities (De Groot et al. 2002; Bateman et al. 2011; Freeman et al. 2014).

Hedonic theory assumes that housing is a composite good, comprised of a bundle of attributes (hedonic attributes). Hedonic attributes may include size, age, physical condition, proximity to services, amenities, or hazards and nuisances. Variations in quantity or quality of such attributes differentiate dwellings from each other (Rosen 1974; Dubin 1988; Sheppard 1999; Brueckner 2011). Rosen (1974) showed that the functional relationship between the price of a differentiated commodity and the vector of its hedonic attributes can be interpreted as an equilibrium outcome from the market interactions between sellers and buyers (Kuminoff et al. 2010). Buyers seek to maximize the utility they derive from housing (Rosen 1974), but due to their budget constraints they substitute one desired attribute for another and adjust the quantities or qualities of hedonic attributes in order to attain their preferred utility level within a budget range. When regressing the price of properties on a vector reflecting the amount or quality of their hedonic attributes, the regression coefficients will reveal the implicit prices of the attributes (Rosen 1974). The prices are implicit—or "shadow" prices—because these attributes are not traded explicitly in their own markets. These prices indicate two features: firstly, the marginal loss or gain of a consumer when a marginal change happens in one of the hedonic attributes, holding everything else constant and given that these are not sweeping city-wide changes (Tyrväinen 1997); secondly, the willingness to pay for amenities and willingness to avoid disamenities (Tyrväinen 1997; Pope 2008b; Kuminoff et al. 2010). On the supply side, sellers will also seek to maximize the profit they make by selling the property (Rosen 1974). In a realized transaction, when full information and full continuity in the levels of attributes is satisfied, the price of a property reflects the meeting of the lower bound of the seller's offer envelop and the higher bound of the buyer's bid envelope for each individual hedonic attribute (Pope 2008b: 553–554). In the long run, house prices will reflect the equilibrium between buyers' demand for hedonic attributes and sellers' "production"—in practice, supply—of those attributes (Rosen 1974), and households will be fully compensated for locational disadvantages.

Figure 2 (left and center) displays hedonic diagrams for an amenity C_i (left) and risk C_j (center), based on Harding et al. (2003) and Pope (2008b). The Figure assumes a linear relation between price and the level of the hedonic attribute and displays two indicative levels of the attribute, noted with * (low level) and ** (high level). For a k-vector of attributes C of a dwelling and for a certain amenity C_i or risk C_j, with $i \neq j \neq k$, the implicit price of the attribute is the equilibrium locus where the seller's bid curve φ and byer's offer curve θ meet. Offer curve φ is a function of the levels of the hedonic attribute and profit, while bid curve θ is a function of the levels of the hedonic attribute, income, and utility (Kumbhakar and Parmeter 2010). The hedonic price equilibrium $P(C_i, C_k)$ or

$P(C_j, C_k)$ assumes that all other attributes C_k are held stable at their own equilibria, although in reality there exist interaction effects between attributes (Harding et al. 2003).

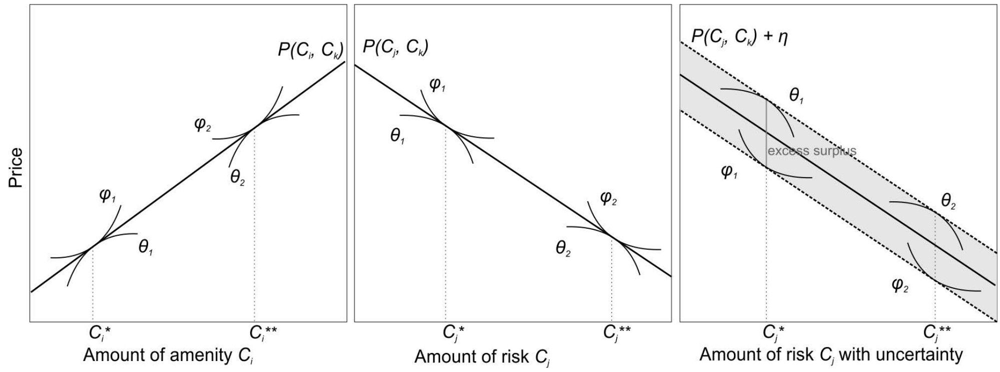


Figure 2: Hedonic prices for a hypothetical amenity, risk, and risk with uncertain information, after Harding et al. (2003) and Pope (2008b).

The estimation of a hedonic price function requires a sample of property transaction data that record each dwelling's selling price and its various structural and location-related attributes. Optimally, the sample should be large and representative of the urban area in focus as temporal and spatial heterogeneity in the housing market are frequently noted as issues that interfere with the estimations (Tyrväinen 1997). Georeferenced transactions, i.e. location-enabled observations, are also increasingly common, because they can be integrated with GIS information layers and spatial analysis methodologies, extending the analytical potential of traditional hedonic analysis. Notable among these extensions is the correction of the estimates from errors due to spatial autocorrelation and the estimation of spatial spillover effects in real estate markets (explained in Section 5.1).

In theory (that is, in perfect markets), price compensation implies that in the long run all similar households are equally well-off at their residential location (DiPasquale and Wheaton 1996). In particular, hedonic price theory assumes full information in the price determination process and no information asymmetries between seller and buyer. In practice, housing markets contain numerous information gaps and asymmetries (Pope 2006, 2008b) that hinder this process. Figure 2 (right) displays what happens to the hedonic price equilibrium under uncertainty about risk C_j. Due to the time and resource constraints involved in the search process, the buyer does not have full access to information regarding the risks of a property and cannot properly assess risk levels. On the contrary, the buyer is assumed to have better access to risk information, often by virtue of living there (Pope 2008b). The result is that the bid and offer curves are no longer tangent; the buyer's bid envelop is higher than the seller's offer envelop, and the price will be anywhere between the respective curves, indicated as a grey area in the diagram. Harding et al. (2003) describe that this results in an excess surplus for the seller, whereas Pope (2008b) describes that the corresponding price $P(C_j, C_k) + \eta$ is the price under full information plus an information uncertainty error η.

In the context of this dissertation, imperfect competition in connection with climate-sensitive risks implies that environmental risks and externalities are not always transparent or assessed properly in market transactions. The marginal values estimated for ecological risks have been approached as indicators of market imperfections and subsequently of the effectiveness of corrective interventions. More specifically, imperfect competition in the case of natural hazard risks implies that mechanisms of the housing markets do not take fully into account climate-sensitive risks. Therefore, the resulting housing prices do not reflect the real, and in some cases quite dangerous, locational disadvantages. The result of this imperfection is the reduced resilience of the housing sector to climate-sensitive risks. The concept of resilience is closely connected to that of adaptation and refers to the difference between society's adaptive capacity and the risk level of a hazard (IPCC 2014). Reduced resilience implies, among others, increased vulnerability to climate-related shocks, since the risks are not fully internalized in key market processes.

On the other hand, the marginal prices of amenities have been used in this dissertation as indicators of how, where, and what kind of investments in ecological land uses are aligned with price formation and compensation mechanisms. This approach is motivated by a sustainable development mentality and relates to aligning climate adaptation goals with economic development goals. Even though the increased use of green infrastructure strengthens an area's climate-proofing capacity by reducing hazard intensity and exposure, its improper implementation can cause the loss of considerable amount of economic value, weakening its economic capacity and therefore increasing its vulnerability to shocks. This problem can be avoided if the conditions under which green spaces generate economic value are properly understood and examined in their spatial and temporal dimensions. Moreover, the utilization in urban planning of green infrastructure for climate-proofing cities *and* for generating economic value is an example of how climate adaptation generates opportunities for cities (cf. IPCC 2014 and Section 2).

4.3. Alternative spatial modelling and simulation approaches

The hedonic approach takes house prices as given and derives submarket formation and differentiation factors for developing policy recommendations. While hedonic analysis is applied in the first three articles of the thesis, the final two articles adopt an alternative spatial modelling and simulation approach. This alternative approach views the city as a whole and uses the insights of the AMM model not only to derive the change of house prices with distance to the CBD and ecological risks and amenities, but to also simulate the possible influences of spatial policies on urban growth processes, notably land use change and the evolution of the built environment.

Motivation for a departure from hedonic analysis is grounded in the fact that the management of climate-sensitive risks and amenities requires an understanding and modification of fundamental spatial processes in the city, as well as an assessment of the implications of such modifications at more than one spatial and temporal scale. The keyword in this case is the optimization of adaptation strategy, which may be described along the lines of Tinbergen's rule: a recommendation may contribute towards a particular objective, but may still need modifications in order to become optimal also within a wider array of urban processes and objectives. Hedonic price analysis cannot provide insights about urban processes beyond the housing market, nor can it assess urban development questions in a spatially disaggregated manner. Additionally, hedonic analysis is capable of capturing market reactions only to strong and immediate changes or signals and can communicate the effects of marginal changes only. Key processes such as urban growth and city-wide land use changes cannot be captured in hedonic analysis, because their gradual or non-marginal nature renders their effects empirically undetectable in markets.

These limitations are characteristic of a historical divide in analytical tools that are available to support urban decision-making: tools have been successful either in generating urban morphologies without the ability to optimize them, or—as in hedonic analysis—in optimizing spatial processes without the ability to reproduce actual urban morphologies (Batty 1997). Similarly, while the management of climate-sensitive ecological risks and amenities ought to consider a reasonably full picture, a bias towards fragmentary approaches has been documented, especially approaches that focus on direct, short-term, and simple cause-and-effect impacts (Meyer at al. 2013; Aerts et al. 2014). The use of modelling and simulation methodologies that stem from complexity theory aims at filling the gap in sustainable urban adaptation research left by hedonic analysis. Complexity thinking—in particular, complex systems and urban complexity theory—is increasingly employed as the overarching framework for understanding and optimizing cities (Batty 2013), in urban adaptation research (Ruth and Coelho 2007; Cumming 2011), as well as in synthesizing the various strains of applied urban research (Batty 2007).

The dissertation utilizes the notion of urban complexity (on the exposition of the spatial modelling and simulation methodologies that stem from complexity science and applied in articles IV and V see Sections 5.2-3). Complex systems are results of the interaction of a number of parts, the function of which as a whole cannot be explained merely through the apparent functions of the parts themselves. The main characteristic of such systems is the impossibility to deduce in any straight-forward way system-wide behaviors, states, and transitions from the properties of the constituent parts. Simon (1962: 468) describes complex systems as systems in which "the whole is more than the sum of its parts, not in an ultimate, metaphysical sense, but in the important pragmatic sense that, given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole." The behavior of a complex system can be simulated in an artificial environment where the constituent parts are allowed to interact freely, but the interactions' results cannot be calculated in advance; they emerge as the system evolves. In this computational process emphasis is placed on the bottom-up constitution of physical, biological, and social systems, and the emergence of elaborate behavior from a simple set of rational rules (Bar-Yam 1997; Batty 2007). The notion of complex adaptive systems adds to Simon's definition the concept of self-modification: as exogenous or endogenous factors change, system behavior also adapts.

Urban complexity applies complex systems theory to the study of urban areas (Batty 2007, 2013). Central in this approach is a bottom-up focus on the spatial interaction, and its temporal evolution, between physical and social components of the city. The theory analyses what happens to a location when nearby locations experience changes, as well as how mobile agents respond to other agents or to their physical and social environment. Based on such interactions, growth processes (e.g. the expansion or densification of the built environment), or evolutionary processes (e.g. land use change and real estate value formation and differentiation) are first modelled and then simulated over time. The data needed for this approach are spatially disaggregated, representing elements of the built environment and the urban economy in high spatial resolution. Frequent resolutions are a few meters to a few tens of meters, although, due to computational requirements, the level of detail also depends on the geographical size of the modelled area. In the case when quantitative analysis is needed before the development of models, the data has to be recorded in relatively regular temporal intervals in order to capture the evolution of the modelled spatial systems. The main advantage of utilizing such data within complex systems methodologies is that it enables a detailed understanding of the effects of spatial policies on different locations of the city and different components of the urban economic system; it also enables understanding the possible evolution of these effects over time. In this dissertation, spatial morphological complexity has been used in application to housing prices in order to show that, while long-run equilibrated processes exist in the spatial configuration of housing prices, when multiple spatiotemporal scales are introduced, the picture is different. In the case of urban growth processes, the results of hedonic analysis were incorporated in a spatial growth model in order to understand the effect of zoning strategies, related to flood risk management, on mid- to long-term urban growth trajectories. Although these effects cannot be captured by hedonic analysis alone, they can be captured and explored by urban simulation models.

5. Empirical methods

Parts of the dissertation research have implemented hedonic price theory and insights of the AMM model through spatial hedonic regressions. The regressions estimated the marginal effect of ecological risks and amenities on house prices. Other parts of the dissertation implemented urban complexity theory via the calibration of cellular automata models and via a novel combination of fractal geometry and co-integration analysis. The former focused on flood risk management and urbanization dynamics, while the latter on the spatiotemporal dynamics of house prices. Although the two families of tools originate in disciplines with notably different theoretical assumptions, the concept of spatial interaction binds them together in the study of spatial economic processes.

5.1. Spatial hedonic models

The most widely used statistical technique for implementing hedonic price theory is the estimation of hedonic regressions. The regressions are typically linear models that express the market price of a dwelling as a function of its attributes. In this context, the estimated regression coefficient of a hedonic attribute is the marginal price of that attribute: a unit change in the quantity or quality in that attribute will modify the price of a typical dwelling by the estimated beta coefficient in the measured units of price. Relating to the AMM model, hedonic attributes have been often categorized as structural, locational, or neighborhood (Dubin 1988). This results in Equation (1), in which $\mathbf{y}$ is a vector of the selling prices of a sample of properties, $\mathbf{S}$, $\mathbf{L}$, and $\mathbf{N}$ are matrices of, respectively, structural, locational, and neighborhood attributes, γ, δ, and ϑ are coefficient vectors, and $\boldsymbol{\epsilon}$ a vector of random errors.

$$\mathbf{y} = \gamma\mathbf{S} + \delta\mathbf{L} + \vartheta\mathbf{N} + \boldsymbol{\epsilon} \quad (1).$$

Spatial econometrics enhances hedonic analysis by introducing spatial interaction between dwellings (in disaggregate observations) or regions (in aggregate data). This is achieved by encoding contingency information in a spatial weights matrix, which lists the neighbors of each observation, typically in a binary manner (1: neighbor; 0: non-neighbor). Neighborhood is identified either through contingency (common nodes or vertices of polygons) or through distance rules (nearest neighbors or a distance radius). The first-order von Neumann and Moore neighborhoods are most often used to determine contingency. For a given polygon, the von Neumann neighborhood identifies the adjacent polygons at the cardinal points, while the Moore neighborhood identifies the complete ring of adjacent polygons surrounding the polygon in question (Figure 3a).

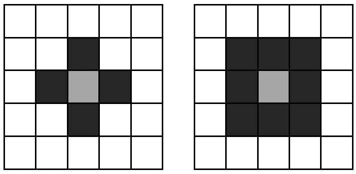


Figure 3a: The 1st order von Neumann (left) and Moore (right) neighborhoods of the central cell.

The concept of order reflects whether the extended neighborhood of a given polygon is included. The first-order von Neumann and Moore neighborhoods do not consider extended neighbors, while higher orders add the neighbors of neighbors (second order), neighbors of neighbors of neighbors (third order) and so on (Figure 3b). In either case, since one's neighborhood has its own neighborhood, and so on, growth and spatial interaction effects propagate gradually in all members of a regional system. Thus, even if the spatial weights matrix may model local contingency, the local processes modelled by spatial econometric tools have global effects, since all elements in a regional system belong to each other's *n-order* neighborhood.

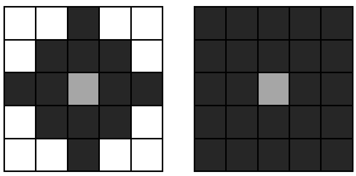


Figure 3b: The 2nd order von Neumann (left) and 2nd order Moore (right) neighborhoods of the central cell. The 1st order neighborhoods of Figure 2a are nested in the 2nd order neighborhoods here, which forms the basis for local interactions having global effects.

Although the above neighborhood rules search for edges and vertices of geometrical shapes, they are applicable also to point observations. This is achieved by computing the Thiessen polygons of points and using the edges and vertices of these polygons to derive contingency. In this dissertation the Thiessen polygon method has been employed in the hedonic regressions of articles I-III whenever disaggregated point observations (individual dwellings) were involved. The main assumption represented by this choice is that each property has equal weight in the competition with surrounding properties in establishing its influence area.

The spatial weights matrix serves as a moving average window (Anselin 1988). The matrix passes over each observation and computes a spatially averaged value in its defined neighborhood, called the observation's spatial lag. The benefit to hedonic analysis is twofold:

Firstly, the majority of hedonic attributes exhibit spatial autocorrelation. This means that locations near to each other exhibit similar values (Tobler 1970). If there are unobserved variables in a regression, then the error will also exhibit spatial autocorrelation and will violate the assumption of identical and randomly distributed errors. Spatial regression addresses this issue by clearing the error from spatial autocorrelation. The most widely used model of this type is the spatial error model, shown in Equation (2), in which matrix $\mathbf{X}$ includes the structural, locational, and neighborhood attribute matrices of Equation (1), β and λ are coefficient vectors, $\mathbf{W}$ is a spatial weights matrix, $\mathbf{u}$ a vector of spatially autocorrelated error terms, and $\boldsymbol{\epsilon}$ a vector of uncorrelated random errors. The nonrandom spatially autocorrelated error that is unaddressed in the non-spatial setup of Equation (1) has been split in the spatial setup of Equation (2) in two components: the spatially autocorrelated component $\mathbf{Wu}$ and the truly random component $\boldsymbol{\epsilon}$.

$$\mathbf{y} = \beta\mathbf{X} + \lambda\mathbf{Wu} + \boldsymbol{\epsilon} \quad (2).$$

Secondly, certain spatial hedonic regressions move beyond clearing the error and exploit spatial autocorrelation to infer spatial behavior in the housing market. The most common behavior of this kind is the interaction between a location or property and its neighboring locations/properties in terms of prices and hedonic determinants. The most widely used model of this kind is the spatial lag model, shown in Equation (3), in which $\mathbf{X}$ is the matrix of structural, locational, and neighborhood attributes of Equation (2), β and ρ are vectors of regression coefficients, $\mathbf{W}$ is a spatial weights matrix, and $\boldsymbol{\epsilon}$ a vector of random errors. In Equation (3), the spatially autocorrelated term is $\mathbf{Wy}$, which is the spatially lagged form of the dependent variable (transaction price).

$$\mathbf{y} = \rho\mathbf{Wy} + \beta\mathbf{X} + \boldsymbol{\epsilon} \quad (3).$$

The main motivation for estimating the spatial econometric models of Equations (2) and (3) is addressing estimation problems that arise from the assumption of non-random residuals due to spatially autocorrelated unobserved variables (Gerkman 2012). This assumption holds in hedonic analysis settings as it is impossible to know from theory or measure all the variables explaining the behavior of agents in the house market or their perception of geographical space. A further motivation is the identification of endogenous spatial interaction behavior in property prices and exogenous spatial interaction behavior in the marginal effects of hedonic attributes. Parameter λ of Equation (2) and parameter ρ of Equation (3) help identify and interpret such effects.

While Kuminnof et al. (2010) concluded that spatial econometric models are among the most trustworthy for hedonic studies, their use is not free of criticism. Identification and causality issues and the uncritical application and interpretation of these models is an area of active debate and the argument reaches deep into the conceptual approach of economic analysis, the policy questions they aim to address, and via what mathematical approaches (see e.g. Manski 1993; Gibbons and Overman 2012). Gibbons and Overman (2012) argue that spatial econometric models should be used in conjunction with strict identification techniques rather than as replacements. In line with their approach, dissertation's article III implements a difference-in-differences identification strategy in a spatial econometric setting, and is thus exploiting the two techniques to their fullest. It is also worth noting that, despite the methodological debates about spatial econometrics, its critical implementation in articles II and III provided estimates that are in line with international and Finnish hedonic literature. The implicit prices of urban green estimated in article II are close to prior Finnish studies that used standard econometric techniques, whereas the flood risk information shock estimated in article III corresponds to independent flood damage cost functions.

The models Equations (2) and (3) differ in their interpretation. In the spatial error model of Equation (2), the estimated coefficients are treated as in ordinary, non-spatial, least squares regressions. The spatially autocorrelated error term is left uninterpretable as it includes the neighborhood effects of unidentifiable variables. In the spatial lag model, the dependent variable is in both sides of Equation (3) and so the estimated coefficients cannot be interpreted at their face value; they contain both a pure and a spatial spillover component (Anselin 2003). LeSage (2008) and LeSage and Pace (2010) propose a multiplier method that renders the coefficients interpretable by dividing them in direct, indirect, and total spatial impacts. Assuming a unit change in a hedonic attribute, direct is the impact on the price of a typical dwelling when that attribute changes in the dwelling itself. Indirect is the price impact when that change happens in the neighboring locations of that dwelling. Total is the price impact when that change happens across the study area concurrently. Spatial impacts are often used to access the effects of policy changes in a spatially interacting system, as in article III of this thesis. Spatial impacts can also be used to assess the opposite direction, as it is done in article II: if an investment is made or an externality is present, spatial impacts trace how much of the capitalization of the investment or impacts of externality is contained at the investment site, and how much of it spills over to neighboring locations.

Spatial econometrics share a fundamental commonality with the urban complexity tools described in the next two sub-Sections (5.2. and 5.3.). The methodology of spatial econometrics to utilize a matrix that encodes neighborhood relationships between observations is, in fact, a first step in introducing an elementary spatial intelligence in the analyzed objects: geographical entities, as well as physical or socioeconomic attributes that these entities might represent, are made aware of their location in a spatial system relative to surrounding entities. Consequently, interaction of these entities is a main factor in the properties and behavior of the system.

5.2. Cellular automata

Cellular automata (CA) are computational tools that model the spatiotemporal evolution of complex systems. Their fundamental assumption is that the aggregate characteristics of a system are entirely the bottom-up result of local spatial interaction and spatial spillover effects (Batty 2007). For urban and regional planning, CA represent a class of computer models with the ability to both reproduce observed urban morphologies and optimize those morphologies according to planning objectives (Batty 1997). Cellular automata are founded upon the work of Turing (1952), von Neumann (1951), and von Neumann and Burks (1966) on self-reproducing phenomena, which helped understand the role of atomic units in the construction and functioning of biological and physical phenomena.

A cellular automaton is a rule-based system that changes states in discrete time. A generic CA consists of the following elements:

- **Cells**: A set of contingent cells arranged inside an n by k lattice,
- **States**: The initial state of a cell and possible states to which it may transition,
- **Neighborhood**: A definition of neighborhood by contingency rules,
- **Transition rules**: A set of ‘if…, then…’ rules that determine a cell’s transition (or absence of) to a new state in time t+1 based on its state and that of its neighborhood in time t.

CA contain what Batty (1997: 267) calls the "generic development principle" of the evolution of spatial systems and which he describes as:

IF *something* happens in a cell's *neighborhood*, **THEN** *some-other-thing* happens to this *cell*.

In the majority of cellular automata applications in the context of urban and regional planning, cells represent land, while the initial and possible states are understood as developed (built-up) and undeveloped (natural) land. Neighborhood is typically defined by the aforementioned von Neumann and Moore neighborhoods (Section 3.1 and Figure 3) or modifications of those, whereas several specialized transition rules are usually involved. Batty (1997, 2007) demonstrates that different combinations of transition rules and neighborhood definitions, as well as the controlled introduction of randomness in state transitions, produces spatial forms that are affine to known urban morphologies. The NetLogo language (Wilensky 1999, 2007) can be used to illustrate alternative CA specifications and the resulting morphologies. These morphologies (Figure 4) show that cellular automata are able to capture basic elements in the growth and morphological variation of real-world urban forms, including the aspect of development cycles.

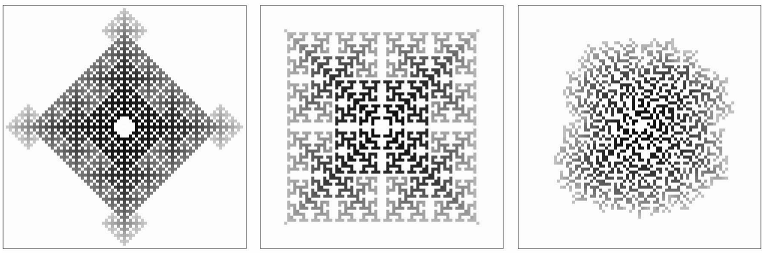


Figure 4: Urban morphologies generated from alternative CA specifications (light grey tones indicate the most recent growth cycles and dark grey tones earlier ones). *Left*: development if only one cell in the von Neumann neighborhood is developed, 39 growth cycles. *Center*: development if only one cell in the Moore neighborhood is developed, 32 growth cycles. *Right*: development if only one cell in the Moore neighborhood is developed and the probability of development is 50%, 32 growth cycles.

Recent advances in CA have enhanced realism and detail in modelling growth and land use transitions in real-world urban systems. The main developments have been: the inclusion of application-specific cell states; the introduction of a greater number of modelled land uses; the ability to model particular urban growth drivers and mechanisms; the inclusion of the transport network's role; and the ability to calibrate models with empirical data (Kim and Batty 2011; Chaudhuri and Clarke 2013). Experimentation with non-binary states and fuzzy transition rules has also contributed to the flexibility and realism of modelling real-world cities. These advances, combined with the rapid increase of computational capacity during the past decades have resulted in the increased use of CA models beyond theoretical explorations and their implementation in operational planning projects. The dissertation has used a highly developed and validated CA model for studying urbanization dynamics and adaptation strategy in Helsinki's metropolitan region. Figure 5 depicts two snapshots of this implementation, illustrating the aforementioned advances in CA modelling: the use of empirical data and real-world built environments; and interaction of urban growth and urban morphology with land use, the transport network, and topographical constraints.

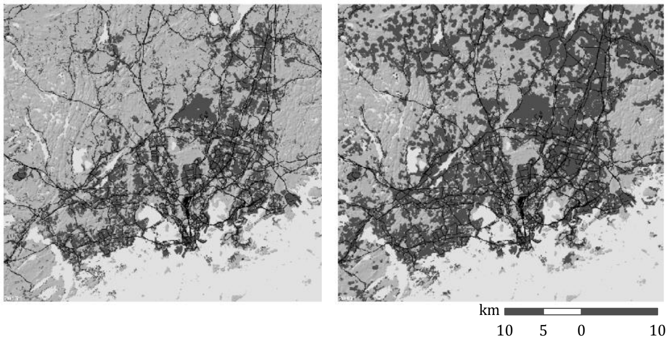


Figure 5: CA model of urban growth in Helsinki's urban region, 2013–2040.

5.3. Fractal geometry

Fractal geometry analyzes the generative structure and morphological characteristics of complex spatial systems. The generalized—non-spatial—context of fractal geometry is that of scaling laws and scaling behavior. Oftentimes two attributes x and y of an object will scale with each other according to an exponent α (Batty 2007):

$$y = x^{\alpha} \text{ (4).}$$

This type of scaling behavior is often seen in growth processes characterized by constraints and competition (Batty 2007) and also characterizes many of the processes reproduced by cellular automata. A common instance of scaling behavior is Zipf's law, which describes the mathematical relation between the size and frequency distribution of cities in a regional system (Zipf 1949; Gabaix 1999). As Equation (4) illustrates, scaling indicates that the percent change of attribute y is proportional, by a certain critical number α, to the percent change in attribute x (Batty 2007):

$$\frac{dy}{y} = \alpha \frac{dx}{x} \text{ (5).}$$

While scaling relationships can refer to attributes of any nature, fractal geometry focuses on spatial scaling behavior. In the geographical disciplines, fractal geometry is an analytical framework that quantifies and characterizes the spatial morphology of man-made or natural geographical entities. While scaling is often characterizing constrained and competitive growth, fractal scaling behavior is additionally related to growth of a multiplicative and bottom-up nature. Key concepts of fractal geometry are those of *fractals*, *fractal dimension*, and *curves of fractal scaling behavior*.

Fractals are mathematical sets that, when visualized, produce shapes that are self-similar across scales (Mandelbrot 1982, 1967). A fractal entity fills space in a self-replicating manner because it grows in a multiplicative way, built additively from an elementary shape. Euclidean geometry cannot describe such a property, because there is no finite edge to be measured. One of the methods to measure fractal behavior is the box-counting or grid-counting method. If a composite spatial object consists of a number of elementary shapes, then a square bounding box with edge length ε can be employed to count the number of elementary shapes N that are contained inside the bounding box. When this protocol of counting N is repeated by increasing ε at specified intervals, one can estimate N as a function of ε, which in its simplest form is (Thomas et al. 2008):

$$N(\varepsilon) = \varepsilon^{\mathrm{D}} \ (6).$$

Parameter D of Equation (6) is the fractal dimension of the measured spatial entity and corresponds to the scaling parameter α of Equations (4) and (6). The fractal dimension ranges from 0 to 2 and indicates, among others, the dispersion, connectivity, and cohesion of a spatial object. Curves of fractal scaling behavior re-utilize parameter ε by assuming that the fractal dimension D also depends on ε (Thomas et al. 2010). This produces a series of fractal dimensions along a continuum of spatial scales and produces the curves of fractal scaling behavior. The curves indicate changes in the fractal dimension from one spatial scale to another and can identify changes in the morphology of a system at certain scales. The curve of fractal scaling behavior of a given built environment has been viewed as its spatial signature (Batty and Longley 1994). As an illustration of the use of fractals in this dissertation, Figure 6 displays three indicative urban morphologies from Helsinki with their corresponding fractal dimension and curve of fractal scaling behavior.

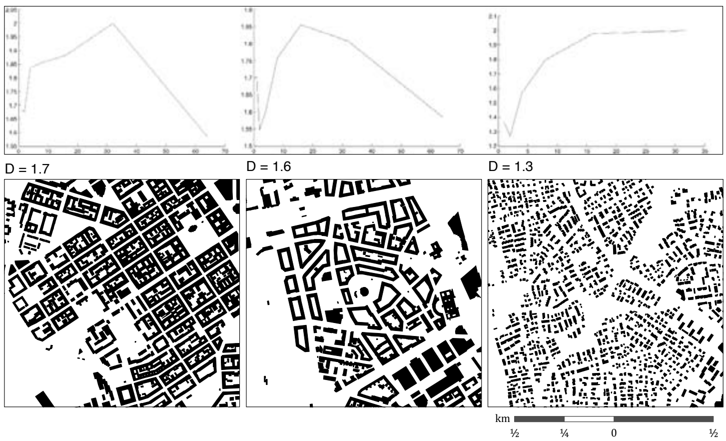


Figure 6: Indicative urban morphologies from central (left, middle) and suburban (right) Helsinki with the corresponding fractal dimension and curve of fractal scaling behavior. The three areas are mapped at the common scale of 1:20000.

Used as an analytical framework, the tools of fractal geometry measure and characterize the property of complex systems of exhibiting organization and order at all spatial scales (Batty 2007). The affinity of real-world urban forms to fractals has been a field of active research. Fractals have been used to quantify and compare urban forms (Thomas et al. 2008) and connect those forms to socioeconomic and historical contexts (Thomas et al. 2012). In economic geography, fractals have been used to study the rank-size distribution of population and other indicators connected to the ranking of cities in a regional system (Frankhauser 1988; Gabaix and Ioannides 2004; Overman and Ioannides 2006). Fractals have also been used to understand the morphology of the built environment across multiple spatial scales and to identify critical scales where urban form changes (Thomas et al. 2010). Lastly, fractal behavior has been linked to the processes reproduced by cellular automata and the two approaches are conjoined for studying the emergence and evolution of cities (Batty and Longley 1994; Batty 2007).

6. Data and ethical issues

A custom, high resolution dataset that records economic, environmental, and infrastructural characteristics of the studied urban areas was developed by the researcher during the first year of the dissertation and first presented in article I. The dataset's components are high quality registered data from official sources. The quality, resolution, and comprehensive nature of the dataset render it internationally high-level data. Despite the abovementioned qualities, the dataset development process has been extensive: the geocoding, data overlay/combining, quality checking, and format conversion and storing operations consumed considerable resources. This step has been crucial for the research, and the effort and challenges involved in developing this kind of interdisciplinary spatial-temporal microdata is often overlooked by analysts who are not involved in data preparation tasks. This Section introduces the thesis' data, study areas, and overall data processing and analysis workflow. Ethical considerations in data handling and analytical research are also discussed.

6.1. Study areas, empirical datasets, and overall research workflow

The thesis relied on empirical data from the housing markets of Helsinki's urban region, Pori, and Rovaniemi, and on geospatial data of land use, topography, the building stock, and infrastructure. These data were used in conjunction or fully merged with each other in order to produce a custom-made dataset. Helsinki region is the capital region of Finland with a population of approx. 1,116,000. Its constituent municipalities are those of Helsinki, Espoo, Vantaa, and Kauniainen. The extended metropolitan area of Helsinki, Greater Helsinki, has a population of approx. 1,500,000 and includes a few additional municipalities. Pori is a city at the west coast of Finland with approx. 85,000 residents (approx. 140,000 inhabitants in its broader urban region). Rovaniemi is a city at the north of Finland with approx. 60,000 inhabitants. Figure 7 displays the three urban regions.

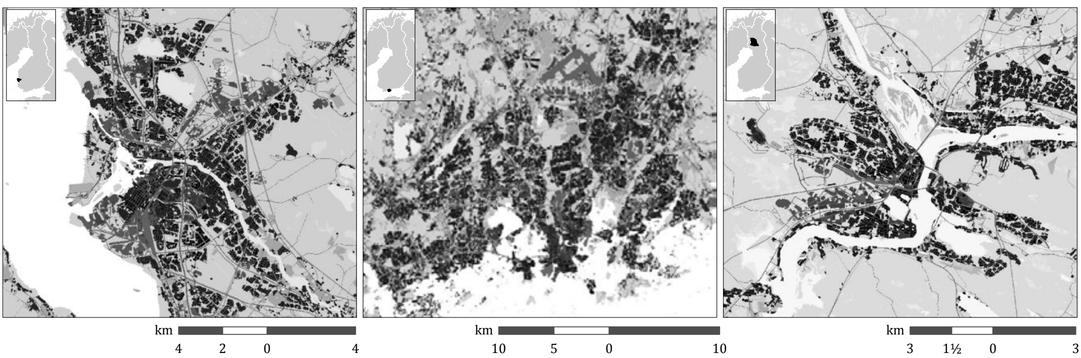


Figure 7: Pori (left), the Finnish capital region (center), and Rovaniemi (right). The insert maps locate the NUTS-3 regions of the three urban areas inside Finland.

The key dataset of the research is a proprietary time series (1970-2011) of housing transactions, acquired and licensed from the Technical Research Institute of Finland Ltd (VTT). The data record the selling price, list/sale dates, address, and structural attributes of a sample of sold properties. The data are voluntarily gathered by participating real estate brokers and are assembled, quality-checked, and maintained by VTT. Beyond the real estate dataset, extensive use has been made of the Finnish National Land Survey's land use dataset (SLICES – pictured in Figure 7 as a greyscale image) and topographic database (Maastotietokanta – its building stock component is pictured in Figure 6). The former is a 10 by 10 meters raster representation of land use in Finland and the latter a vector representation of the man-made and natural landscape of Finland at the scale of 1:10000. Additionally, GIS versions of official flood risk maps for various Finnish cities were provided by the Finnish Environment Institute. Various auxiliary data complemented the analysis, notably variables from the national and regional economic accounts by Statistics Finland and EUROSTAT.

Figure 8 displays the general workflow of data, preprocessing, and analysis. Land use and real estate information were merged to produce hybrid socioeconomic-biogeophysical datasets. The housing transaction data were georeferenced by using the properties' street addresses and stored as point features in a GIS dataset. The attribute table of the transaction points (i.e. the original, non-spatial hedonic attributes) was expanded to include proximities to various land uses, services, infrastructure, and topographical features. Similarly, the flood risk maps were used to categorize properties into flood-safe and flood-prone classes and to subsequently analyze this categorization in connection to housing prices and hedonic attributes. Lastly, the land use and topographical data were used in developing a multitemporal dataset of land uses and the transport network. Zoning and growth constraints were derived from land use data and planning agencies, whereas topographical parameters were derived from the National Land Survey's 10-meter digital elevation model.

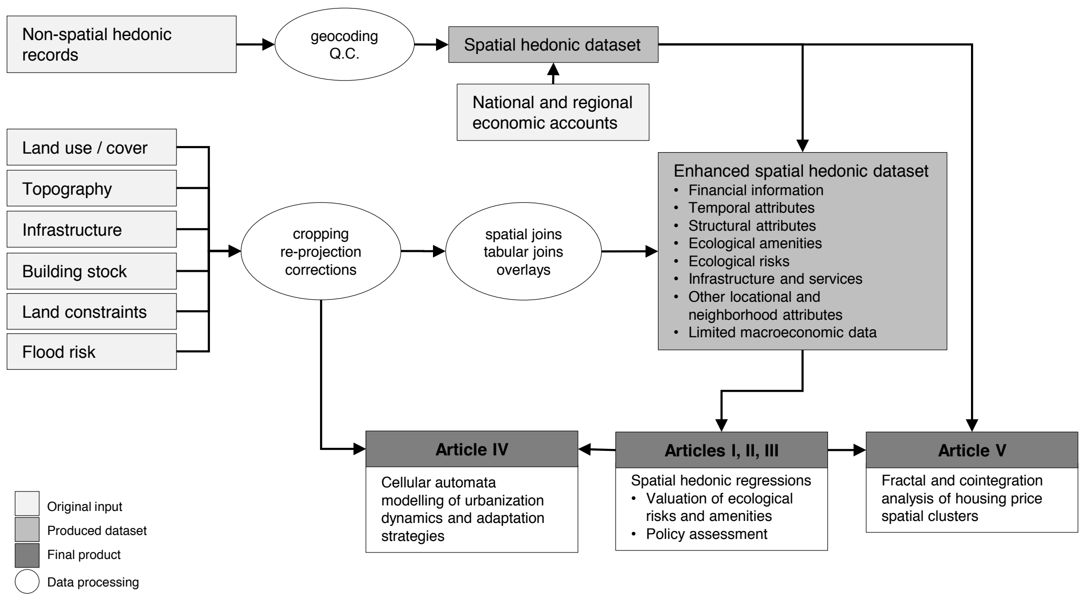


Figure 8: Main data processing and analysis workflow of the thesis.

The GIS data are stored in the ETRS EUREF-FIN projected coordinate system, which is the current official coordinate system of Finland and complies with the EU INSPIRE directive. A small portion of data is stored in the formerly official YKJ (KKJ zone 3) projected coordinate system. The spatial analysis prioritized data that have EUREF-FIN as their native coordinate system. In a few cases where data could be acquired only in the YKJ system, re-projections were performed. The error in these transformations is insignificant for the type of economic processes studied by this research.

A particularity of spatial analysis with housing transaction data is the handling of what seems to be duplicate observations. These duplicates refer to points with exactly the same coordinates, but which correspond to factually different market transactions. These cases result from multiple market transactions involving either repeatedly the same dwelling during its lifecycle, or multiple properties (for instance, apartments) at the same address. These duplicate points cannot be handled appropriately by the utilized spatial econometric tools, so a procedure was established that preserves the duplicates while displacing them by (i.e. moving them apart) a few centimeters. In practice, the distance is so insignificant that this has no effect for the modelled mechanisms, since the mechanisms have been captured in the scale of a few to tens or hundreds of meters.

6.2. Data privacy and ethical issues

Even though the data used for the dissertation research do not contain sensitive information, there are some risks involved in handling the data. Each real estate transaction record contains the address of the sold property. In theory, combining the address and date of transaction, it is possible to identify the household(s) involved in the transaction, revealing potentially sensitive information. Such information may include, for instance, the various financial and structural characteristics of the sold property. No names, contact information, or identification numbers are included in the dataset. Neither does the dataset include demographic or financial information about the seller and buyer. However, technically skilled analysts with several spatial datasets at their disposal could pinpoint the particular demographic characteristics of the particular neighborhood in which the transaction happened. Unless multiple security breaches take place in several organizations that handle interconnected datasets, it is not possible to identify particular individuals.

Due to the above considerations, and in coordination with the real estate data proprietor (VTT Ltd), the research took four precautions to protect the data. Firstly, the data are stored in a password-protected device not accessible to the intranet or internet. Geocoding, which requires internet access, was performed by removing all the information from the data and keeping only the address and a custom-made unique identifier for each transaction. Once those records were geocoded into points, they were re-joined offline to their vital information. Secondly, analysis involving the data is conducted with no access to the internet. In both cases above, the computer processing the data is additionally protected by a firewall that is part of the Finnish government's ICT infrastructure. Thirdly, the quantitative and qualitative results are communicated as aggregate results, usually referring to no less than a few hundred observations. Although the minimum level of aggregation was agreed with VTT Ltd at eight observations, the results have not discussed such a low level of aggregation. The presentation of the research results is not specific enough to enable one to deduce sensitive information about particular housing properties. Similarly, maps, figures, and images do not display identifiable disaggregate points. Lastly, all published results are reviewed by the data proprietor and approved as keeping the formal security and ethical requirements.

The rest of the datasets involving descriptions of the physical, natural, and social environment do not involve information that is considered sensitive or harmful to individuals. All of these data are in the public domain, of secondary nature, and have been handled extensively by responsible agencies and organizations in Finland or other European countries before being downloaded and used in the present research. Aside from data privacy in relation to secondary datasets, the research did not involve collection of primary data and information or other research interaction with human subjects or non-human species. Full credit has been given to the sources of data, theories, methodologies and other materials via the academic articles in which they were used.

There are less technical and more philosophical ethical considerations related to possible misuse of the conducted research by third parties. For instance, how can one ensure that a recommendation for honoring the economic benefits of agglomeration is not misinterpreted as an implicit suggestion that the economy is prioritized over the environment? Conversely, how can one ensure that a criticism to market mechanisms that deteriorate urban ecosystems is not misread as an activism statement? Such inquiries are too abstract in their nature to be a scope of technical research such as the present dissertation; they belong rather to the domain of theoretical sciences. However, in accordance with best ethical practices, the dissertation research has been informed about these broader ethical issues and they have served as guidance in conceptualizing, interpreting, and presenting the quantitative results. The general stance towards such issues in the thesis is this: the sensible use of the presented analytical results should be considered as a main social responsibility issue. As mentioned throughout this text, the results of this thesis should be considered as parts of a wider array of problems, phenomena, and objectives. The mere fact that real estate prices rise or decline as the result of changes in the physical or social environment must not be taken in isolation; by itself, it conveys no meaning and no policy recommendation should be made based on this fact alone.

6.3. Unavailable data

The study would have benefited from a longer time series of land use and infrastructure maps of the study areas. Public high resolution land use data extend from 2000 to 2012, while the property transaction records that were available for this research extend from 1970 to 2011. This meant that hedonic valuations could only estimate the shadow prices of ecological attributes starting from approximately 1995, whereas the records from 1970-1995 could not be fully utilized. The implication is that 25 years of temporal variation in the implicit prices of risks and amenities could not be retrieved. The availability of these data would have enabled the estimation of demand determinants for risks and amenities in articles I-III. In addition to an extended times series of land use maps, article III would have benefited from property transaction records after 2011. This would have enabled a longer tracking of market responses to risk-related shocks, providing information, among others, on memory effects and risk information decline in the housing market.

7. Results

7.1. Results of the individual articles

The first three dissertation articles study the spatial economic effects of climate-sensitive risks and amenities on housing prices. The fourth article explores the links between urbanization dynamics and flood risk management. The fifth article focuses on the aspects of in- and out-of-equilibrium behavior of housing prices at multiple spatial scales that are not always captured in spatial economic analysis. Table 1 provides a list of the articles with their methodologies and data. This Section starts with notes on the interpretation of the results and proceeds with summarizing the articles' results, while their synthesis is presented in the next Section (the content of the articles is described in Section 1).

Table 1: List of articles and corresponding methods and data.

	Name	Method	Data
I	Ecosystems and the spatial morphology of urban residential property value: a multi-scale examination in Finland	Hedonic price theory; spatial econometrics; GIS analysis	Housing transactions; land use
II	Planning for green infrastructure: the spatial effects of parks, forests, and fields on Helsinki's apartment prices	Hedonic price theory; spatial econometrics; GIS analysis	Housing transactions; land use
III	Housing prices and the public disclosure of flood risk: a difference-in-differences analysis in Finland	Hedonic price theory; difference-in-differences analysis; GIS analysis	Housing transactions; flood risk maps; land use
IV	Utilizing the SLEUTH cellular automaton model to explore the influence of flood risk adaptation strategies on Greater Helsinki's urbanization patterns	Urban complexity; cellular automata; GIS analysis	Land use; transport network; topography; development constraints; flood risk maps
V	Exploring the spatiotemporal behavior of Helsinki's housing prices with fractal geometry and co-integration	Urban complexity; fractal geometry; time-series analysis; GIS analysis	Housing transactions

It should be noted that the results cannot always be interpreted in a clear-cut manner. Given the theoretical foundation, data, and methodologies applied in this research, one should ask to what extent the results are good tests of the hypotheses and how clear the impacts are of/to the key variables of interest. In this sense, article II provides a tested confirmation of the hypothesis that urban green spaces increase the inherent economic value of residential real estate, which is in line with Finnish and international hedonic literature. The results of article III provide well-tested evidence that the real estate market processes official flood risk information fairly accurately to better reflect the level and spatial distribution of flood risks. The results are in line with international literature in two aspects: with studies that show that information on upcoming changes in environmental externalities or urban policy changes have a detectable effect on property prices, as well as with studies that show that the housing market is clearly subject to the opposing drivers of coastal amenities and coastal risks. On the other hand, article V provides a tested confirmation of the hypothesis that the spatial and temporal distribution of house prices exhibits non-trivial differences across spatial scales and follows an evident in- and out-of-equilibrium behavior, which is in line with the work done in the emerging field of urban complexity. Articles I and IV are more exploratory and their results serve as supporting evidence or extensions for articles II, III, and V; they show that while complex spatial processes in themselves can be difficult to interpret, when they are combined with different impacts and policies, they can lead to significantly different urban futures. Article IV in particular, confirms prior literature in computational urban analysis that spatial simulation models can be portable and that their first principles approach, free of overly constraining theoretical assumptions, can introduce a much needed perspective in questions that are increasingly asked in sustainable and climate-proof urban planning: how will an urban area evolve over space, following certain policies, and how do alternative policies compare to each other?

The existence of complex spatial processes and the identification of cause and effect relationships is a general problem of most urban studies. Even with comprehensive high-quality data, it is somewhat naïve to claim causal relationships in urban systems; i.e. a setting that enables straightforward interpretation is not always feasible in urban analysis. The presence of complex spatial processes in urban areas means a tremendous degree of endogeneity in relationships between variables, where one change leads to a chain of other changes across spatial and temporal scales. Thus, while the results of this dissertation can be taken as tested verifications of the abovementioned hypotheses, interpretation in the context of urban planning and urban policy should always proceed with caution. The application of hierarchical multi-scale, multi-model planning support systems—which are often more clear for policy purposes—is the subject of further research; the present dissertation aimed to confirm fundamental mechanisms, identified lesser known ones, and drew empirical links between sustainable and climate proof objectives. The dissertation's articles can be also seen as studies that unravel details, so that more complicated models can be refined. Despite the above uncertainties, the analysis has been able to bring new information about complex spatial processes. As a whole, this research confirms the hypothesis that, while ecological risks and amenities have identifiable impacts on house prices, the spatial complexity behind those impacts is non-trivial: if sustainable climate-proof urban policy is to be successful, it has to engage in spatially and temporally parameterized analysis.

Article's I main task was to develop georeferenced hedonic datasets and derive hedonic models from the datasets for Finish housing markets, with special reference to climate-proof sustainable urban planning. The article implemented hedonic regression models in order to understand the spatial character of the role of ecological amenities in residential property value formation and differentiation. The analysis included estimations—at various spatial scales—of spatial hedonic functions on data from the cities of Helsinki, Espoo, and Pori. Data and hedonic models were then fine-tuned for the specific needs of articles II-V.

The results of article I indicate that the natural land uses that enter the hedonic function vary as one moves from citywide spatial scales (e.g. city districts, postcode zones) to local spatial scales (e.g. city blocks, individual properties). It appears, as Figure 9 shows, that this variation has a hierarchical logic, which provides a hint of multiscale hierarchies and could illuminate the relation between the AMM and hedonic approaches. It is difficult, however to draw more detailed conclusions as comparing the marginal prices for different levels of aggregation is not straightforward; these hedonic regressions were not set-up as nested models, but were independently estimated for each spatial scale. The article treats the differences in the statistical estimates for the shadow value of ecological amenities across scales of measurement as a result of differences in perception: amenities at fine scales are perceived in the housing market as ontologically different entities than amenities at aggregate scales, and therefore hedonic models at each scale uncover fundamentally different mechanisms. The connection of this phenomenon with the modifiable areal unit problem (MAUP; see e.g. Briant et al. 2010) is beyond the scope of the article. Vertical variation across spatial scales is complemented by two horizontal distance decays at every scale: a logarithmic decay of the marginal price of amenities when moving away from the amenity, which is in line with the applied hedonic literature (see Section 3); and a linear dependence on distance to the city center, which is in line with the AMM model. Next to spatial variability, the estimated marginal values exhibit notable temporal variation, even after using de-trended prices, indicating a dependence of the marginal willingness to pay for amenities on wider economic conditions (e.g. national and regional economic performance), or changing perceptions on the natural environment (e.g. perceived availability of green spaces). However, these temporal aspects were not explored further as the time series of the estimated marginal prices is not substantial.

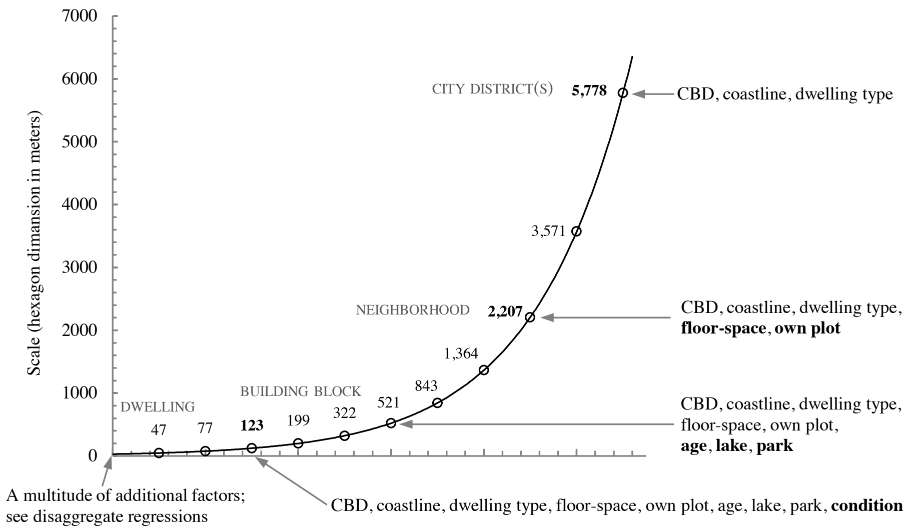


Figure 9: Price differentiation factors in Helsinki and Espoo. New factors at each scale are shown in bold.

The results of article I, on one hand, confirm the idea that ecosystems *consistently* enter price formation and differentiation at various spatial scales, i.e. their role in the housing market is structural. On the other hand, the article shows that the economic benefits of ecological amenities have to be considered in specific spatial and temporal contexts in order to boost the economic benefits of using green amenities in planning or adaptation strategies.

Article II elaborates on the abovementioned general conclusions and focuses on conditions under which the spatial implementation of green infrastructure capitalizes positively in house prices. From an urban planning and economics perspective, this raises a spatial question: if more land is allocated to ecosystems, how do the economic effects propagate throughout urban space? The article explores a possible answer to this question by estimating spatial error and spatial Durbin hedonic models on a large sample of apartment transactions for the period 2001-2011 in Helsinki. The estimation results identified the type of urban green that capitalizes positively in house prices, the distance bands from the city center at which this phenomenon occurs, and the type of spatial spillover mechanism via which it happens. This information is regarded in the article as an important dimension of the abovementioned issue of optimal allocation of green space. Methodologically, the article demonstrates how spatial econometrics can be critically applied in conjunction with mainstream econometric identification strategies (see Gibbons and Overman 2012).

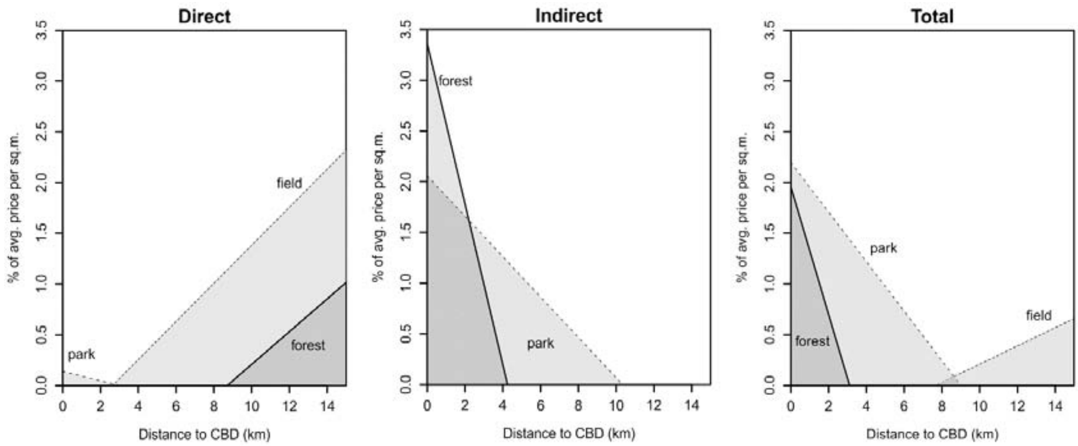


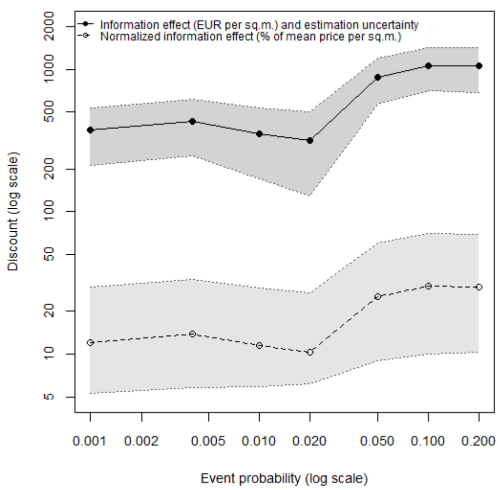
Figure 10: Spatial marginal effects of forests, parks, and fields on a typical apartment.

The results of article II indicate that investing in green infrastructure will have varying marginal effects on prices and that it is not possible to advise an unconditional implementation of green spaces, as some implementations may hurt the housing market. The article describes three factors upon which this variation depends. Firstly, the capitalization of urban green in apartment prices exhibits a significant urban-core-to-fringe gradient, i.e. the marginal price of urban green is a function of distance to the city center. As in article I, this price gradient is in line with the predictions of the AMM model and results of past hedonic studies, but also concurs with literature that discusses a density argument in relation to the value of green (see Section 3). Secondly, the level of the marginal price effect depends on the type of implementation, i.e. whether a green patch is predominantly forest, park, or field. Thirdly, the price effects spill over to and from neighboring locations. More specifically, the analysis indicates that the price benefits of a certain urban green type may originate from (and, consequently, spillover to) neighboring properties at certain distances from the city center. When moving to another distance band from the city center, the spatial mechanisms of the generation of price benefits for the same type of green space may change. Figure 10 summarizes the characteristics of these spatial spillover effects.

As discussed in the article, the variable "distance to the city center" should be handled with care. It is a compound proxy for various causal processes that co-determine the valuation of urban green, such as density, scarcity of natural amenities, intensity of agglomeration externalities, and urban development trends. Distance to the CBD should, therefore, not be interpreted uncritically as a cause of the changing valuation of urban green, but as a proxy of the mentioned processes. Identifying more straightforward cause-and-effect relationships would be interesting future work;

this would require, however, a change of methods and the use of multisector spatial simulation models that require resources beyond the scope of this dissertation; nevertheless, articles IV and V serve as a groundwork for such future work.

Article III explores imperfect information about flooding risk in urban coastal housing markets. In such markets, the amenity dimension dominates the risk aspect, and this fact poses a clear challenge for the resilience of housing markets to the impacts of climate change. The challenge lies in the fact that the dominance of "risky amenities" attracts growth in hazardous locations—as has also been confirmed by the urban growth simulations in article V—whereas the coastal housing market may not reflect the actual level of risks. The article explores the disclosure of flood risks through maps as a policy instrument aimed at addressing this situation. The paper assesses the effectiveness of this policy instrument by identifying whether such maps induce a price differential for single family coastal dwellings in three Finnish cities and by estimating the discount per square meter for various flooding probabilities (return times). The article also explores behavioral aspects in the mechanism of flood risk discounting, namely the bounded-rational relation of price discount to risk level, and the correspondence of the price discount to flood damage curves.



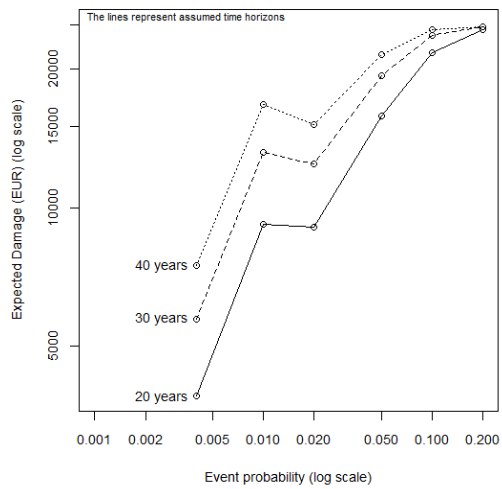


Figure 11: Left: sensitivity of the information effect to sea flooding frequency; right: expected flood damage for a typical dwelling in Greater Helsinki's coast by flood return times.

The estimations reveal a price drop for those properties which were indicated as flood-prone by the maps after the disclosure of risk information. Such behavior was detected in three different cities at different points in time. In Helsinki the information concerned sea flooding; in Pori and Rovaniemi it concerned river flooding. In the case of sea flooding information in Helsinki, the price effect was sensitive to the probability of flooding (Figure 11 left). More specifically, properties subject to more frequent/probable floods exhibited a higher price drop than those subject to less frequent/probable floods. The price drop – flood probability curve was found to correspond to independently calculated damage costs for different flooding return times. This correspondence provided an indication about the way homeowners discount properties in connection to flood risks and the expected financial burden of flood damages (Figure 11 right). The detected response is non-linear and exhibits bounded-rational behavior. Firstly, the price discounts of very high probability floods tend to be overestimated, while those of very low probability floods tend to be underestimated. Secondly, there is a clear rise in the price shock once the threshold of 50 years is crossed, i.e. floods expected to occur at least once in 50 years or less. This presumably relates to the duration of benefits that homeowners expect from a dwelling and shows that risks that are within their planning horizon are more relevant in property transactions than risks that potentially induce high damage costs, but are rare and beyond the planning horizon.

Overall, the information dissemination as a policy instrument appears to have functioned as intended, correcting information gaps and asymmetries related to flood risks. The identified effect was spatially selective; it caused a short-term localized shock in market prices with some reorientation of demand from risky coastal properties towards ones that represent a similar level of coastal amenity, but are less risky in terms of flooding. This hinted at the potential for incorporating the shocks associated with flood risk information into broader-scoped urban modelling and simulation (this aspect is explored in article V). Similarly, the reasonable accuracy with which the housing market processed the additional information shows a potential for wider use of the disclosure of non-obvious risks in real estate markets.

Article IV calibrated the cellular automaton model SLEUTH in order to explore how mid- to long-term urbanization parameters are impacted by alternative flood risk management strategies. The model was implemented in the urban region of Helsinki at a 50x50 meters spatial resolution, annual time steps, and a forecast horizon until 2040. The baseline urban growth trajectories were compared to the results of two sets of growth regulation strategies. The first set translates property price effects of flood risk information (estimated in article III) into various attraction-repulsion areas in and adjacent to the floodplain. The second set explores varying degrees of straightforward restriction on new growth in the flood risk zones without letting market responses guide land regulation. As discussed in Section 3, the simulations tested different assumptions about the planning system's relationship to market forces, ranging from adjusting to constraining them, but a fuller modelling of this relationship is out of the dissertation's scope.

The simulations indicate that the current urbanization trend in Greater Helsinki is characterized by moderate growth rates, which are realized in space as a continuous expansion and infill of existing built-up land driven by edge and road-transport growth. Interestingly, the most intense growth of built-up land is expected to happen in flood risk areas (Table 2). The hedonic estimations in articles I and III that indicate the strong influence of coastal amenities in the housing market confirm this prediction, given that residential real estate is the biggest component of new growth in the urban region of Helsinki.

The scenario simulations aimed at restricting the aforementioned trends in various ways in connection to the spatial distribution of flood risks. First of all, the results of the scenario simulations indicate that restricting growth inside the floodplain also slows urbanization in the broader region, unless growth is actively re-oriented into a specific area. The restricted growth potential inside the floodplain does not appear to be re-channeled elsewhere, but remains latent in the system for a few decades. Next, the tested scenarios registered a few distinct differences in the way they impact urban growth. Those that place milder and more targeted constraints on urban growth recover—and in some cases exceed—the baseline trends within the forecast horizon, whereas stronger and non- spatially selective restrictions appear to simply subdue growth in a more permanent fashion. The spillover of the impacts of different policies outside the application area varies among scenarios (Figure 12).

Table 2: Baseline forecasts for year 2040 for near-coast areas based on a 90% threshold of the cumulative urban probability map.

	Built-up land in 2040		% change from 2012
Zone	*pixels*	*hectares*	
F5	4636	1159	66.0
F10	422	106	47.6
F20	429	107	44.0
F50	584	146	46.0
F100	1640	410	69.6
F250	635	159	30.4
F1000	1175	294	41.4
Flood-safe (0.3 km from coast)	8226	2057	18.6
Flood-safe (0.3-1 km from coast)	96415	24104	39.9
Flood-safe (1-10 km from coast)	16211	4053	24.0

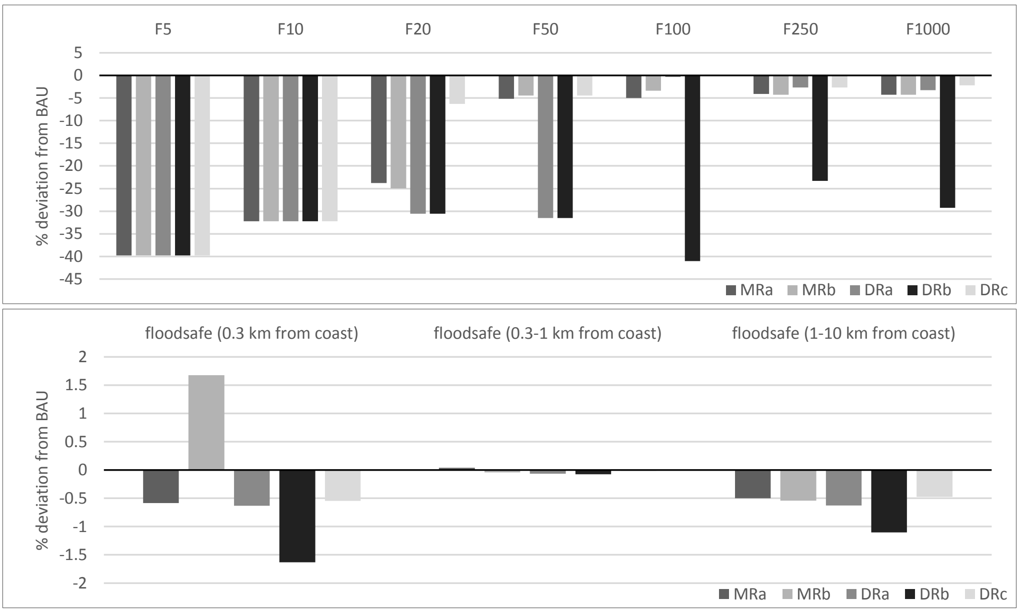


Figure 12: Scenario deviations from BAU in total built-up land in year 2040 in flood-prone (top) and indicative flood-safe areas (bottom).

The scenario comparisons show that attuning spatial growth restrictions to the differences between flood zones—either by referring to market indicators (in this case, shocks in housing prices from article III) or by gently following the spatial morphology of flooding probabilities themselves (therefore bypassing market behavior)—has milder impacts on urbanization than more sweeping spatial restrictions. This highlights the question of economic-environmental trade-offs in sustainable urban adaptation: after assessing how urban growth responds to flood management policies, one has to ask whether more or less growth is desirable. Although, answers to this question would require more extensive spatial economic modelling than this dissertation aims at, the SLEUTH model is able to make a clear contribution by quantifying and geographically locating urban growth indicators for alternative strategies. Thus, the results of article IV demonstrate that spatially disaggregate urban simulation adds an important integrative aspect to urban adaptation studies, translating general socioeconomic strategies into concrete context-specific impacts and opening links to more comprehensive multi-process and multi-sector model ensembles.

Article V is the most theoretically oriented in the thesis. Compared to the AMM and hedonic approaches, the article undertakes a closer and more detailed examination of the spatial and temporal behavior of realized housing prices as they had been distributed over Helsinki from 1977 to 2011. The paper proposes a novel combination of fractal geometry and co-integration analysis. As discussed in Section 5, fractal geometry is a unique, non-Euclidean measure of spatial behavior that can be used in urban economics, because it is the only indicator that can describe how property value progressively fills space as it grows. It is not a measure of density, dispersion, or other Euclidean concepts, although it can be used to describe these concepts, too. Its use in article V, in conjunction with co-integration analysis, aimed at describing equilibria and disequilibria in the growth process of price/m^2 clusters.

The analysis first identified spatial clusters of high and low price/m^2 values in Helsinki's urban area for each quarter by using a hot and cold spot analysis methodology. For each quarter's clusters of high and low /m^2 prices, curves of fractal scaling behavior were calculated in order to derive the fractal dimensions of high and low price/m^2 clusters at the spatial scales of 100, 200, 400, 800, 1600, 3200, 6400, and 12800 meters. Lastly, the time series of the fractal dimensions at indicative neighborhood (200 meters) and city-wide (12800 meters) scales were modelled with vector error correction setups. Each setup estimated the endogenous quarterly dynamics between the fractal dimensions of high and low price/m^2 clusters. The proposed analytical framework aims to offer a way to explore the interrelationship between equilibrated and disequilibrated behavior of areas of high and low property prices at each scale.

The results of article V, summarized in Table 3, indicate that, although a long-term equilibrium between the spatial morphologies of high and low price/m^2 value characterizes both spatial scales, the dynamics are substantially scale-sensitive. The fractal geometry of high price/m^2 clusters leads the dynamics at the neighborhood scale, in which high value clusters exhibit higher fractal dimensions than low value clusters. External shocks in the spatial morphology of high price/m^2 areas induce permanent shocks in the system and cause the morphology of low price/m^2 areas to adjust in order to restore the joint equilibrium. This situation is reversed at the city-wide scale, in which the fractal dimensions of low value clusters are higher than that of low value clusters. There, the fractal dimension of low price/m^2 areas leads the dynamics, with the fractality of high price/m^2 areas adjusting to disequilibriations. The lead role of high price/m^2 areas at the neighborhood scale is in line with the AMM model's view that the high bidders lead residential location dynamics, and consequently the formation of the geographical morphology of property prices. Interestingly, the finding of this study about the lead role of low price/m^2 areas at the city-wide scale concurs with other co-integration studies in the property prices of Helsinki's urban region.

Table 3: Estimated endogenous dynamics between the fractal dimensions (D) of high and low price/m^2 areas at neighborhood and city-wide scales.

	Neighborhood scale (200 m)	**Citywide scale (12,800 m)**
Fractal geometry	$D \approx 0.7$ for high price/m^{2}clusters and ≈ 0.2 for low price/m^2 clusters. Quarterly volatility $\approx$ +/– 0.2 in both price/m^2 categories; $I(1)$ non-stationary series.	$D \approx 0.5$ for high price/m^2 clusters and ≈ 1.3 for low price/m^2 clusters. Quarterly volatility $\approx$ +/– 1 for high price/m^2 clusters and $\approx$ +/– 0.3 for low price/m^2 clusters; $I(1)$ non-stationary series.
Long run equilibrium	D of high price/m^2 clusters is approx. three times that of low price/m^2 clusters.	D of high price/m^2 clusters is approx. 0.4 times that of low price/m^2 clusters.
Short run adjustments	Led by high price/m^2 clusters. Low price/m^2 clusters adjust to short run fluctuations of high price/m^2 clusters to restore joint equilibrium. High price/m^2 clusters do not adjust.	Led by low price/m^2 clusters. High price/m^2 clusters adjust to short run fluctuations of low price/m^2 clusters to restore joint equilibrium. Low price/m^2 clusters do not adjust.
Orthogonal impulse responses	High price/m^2 clusters have permanent effects. Low price/m^2 clusters have near transient effects. Effects stabilize in 20 quarters.	High price/m^2 clusters have transient effects. Low price/m^2 clusters have permanent effects. Effects stabilize in eight to ten quarters.

The results of article V firstly highlight a clear need to capture in more detail the variation in house prices, if prices are to be used as indicators in urban adaptation and sustainable planning. Increased detail refers to a deeper understanding of temporal processes, but also to the consideration of more than one spatial scale. This need arises from the fact that fundamental aspects of the behavior of prices appear to differ from one spatial and/or temporal scale to another. Secondly, the results open up a theoretical question about the precise relationship between scales and the processes modelled by the AMM and hedonic approaches: can we, for instance, correspond some of the dynamics identified in this article to a particular model? While a first response to such granularity is to separate the various equilibrated and disequilibrated mechanisms contained in the end-result of housing prices, from a sustainability viewpoint it is rather important that price behavior at household-specific scales differs from the behavior at zonal scales. Nevertheless, this article aimed at opening up, rather than resolving, questions of spatial complexity in the geographical behavior of property value. The article's utility should be understood as one of the few attempts in the urban economic literature to quantitatively model multiscale temporal and spatial behavior with state-of-the-art complexity indicators; opening up the use of fractals in this field is particularly important, as there is no other indicator than can provide a quantitative typology of the morphology of spatial growth processes.

The policy and decision-making questions raised by the findings of the dissertation articles are discussed in more detail in Section 8, which aims to synthesize the results, placing them into the context of planning a climate-proof, sustainable city.

7.2. Limitations of scope and employed methodologies

This dissertation is based on the assumption that a fundamental strategy in linking questions of sustainable development and climate-proof planning is to place these questions inside the issue of why cities exist and evolve as they do. Key determinants are: nature, including the landscape; market forces based on location; choices of households and firms; the public sector through urban planning, zoning, and urban policy; and history, since much of the city is durable capital and major changes take time to be visible, even though many sub-processes are highly volatile. This research takes the city as given with all the other determinants, while focusing mainly on markets and the landscape. This assumption limits the explorations of the relationship between market forces and the planning system (i.e. the public sector). For example, the analysis tracks market responses to marginal changes of ecological land uses (articles I-II) or flood risk public policy (article III) as well as the long term spatiotemporal evolution of housing prices (article V) by assuming the planning system as given. As a result, articles I-III and V do not address the issues of land use and planning practices, as well as the political institutions driving these practices. Questions of whether the planning system constraints or adjusts to market behavior, how much, and for what reasons, are also left out as they are the object of a different research. Similarly, when urban processes are examined over time in article IV, alternative assumptions about the planning system's response to market behavior are tested to the necessary extent, but the in-depth analysis of the planning system is the object of a different research.

The dissertation does not offer a detailed exploration of the concept of ecosystem services. Such questions as the formal distinction between ecosystem services, ecosystem functions, and service-providing land uses fall outside the scope of the thesis. Instead, articles I-III assume that ecosystem services are necessarily tied to major types of natural land use in urban areas and opted to study the spatial effects of those land uses in the housing market. The dissertation rests on the underlying assumption that there is more sense in analyzing bundles of ecosystem services that are contained in (or represented by) land use classes, rather than to dissect the services into atomic units. Adopting such a perspective on the research problem, the dissertation prioritizes providing valuable information about the sensible implementation of natural land uses in urban areas, which is always tied to land use planning and its economic effects. Those questions that may be important in socioecological research are, thus, not in the focus of the present study. This assumption is justified by goals and visions of the discipline of urban planning, but also supported by hedonic valuation studies (e.g. Czembrowski and Kronenberg 2016).

The dissertation aims at demonstrating linkages between adaptation and urban planning, and how these links can be facilitated by a class of applied urban research that combines urban economics and spatial analysis. As a result, from the viewpoint of research in economics it might be argued that the dissertation research lacks sufficient detail in interpreting economic behavior. However, from the viewpoint of applied urban research, which is the field in which the dissertation is conducted, the research has the benefit of deeper understanding of complex spatial processes.

Furthermore, this dissertation does not discuss its results in connection with the idea of polycentric cities. In most of the conducted studies, the question of mono- or poly-centricity was interesting, but not relevant. Moreover, it is arguable whether a given city is to be modelled as polycentric or as a conglomeration of smaller monocentric cities. It is likewise debatable that a research that assumes the city to be polycentric will produce significantly different practical results from a research that assumes it monocentric. Similarly, the dissertation does not consider the application of its results to spatial configurations of human settlements that are radically different from the selected study areas. Theorizing about alternative spatial urban arrangements is a matter of separate research beyond the scope of this study.

As far as methodologies are concerned, a number of limitations must be noted. Although different parts of the research have referred both to the AMM model and hedonic price theory, it will be worth in future research to expose in more detail the way in which these models relate to each other. While both theories are founded on microeconomic principles, the former is a model that operates with urban *areas* while the latter operates with individual *dwellings*. In terms of real estate prices, the former focuses on their city-wide price *formation* and accepts only a few key factors of differentiation, while the latter does not treat city-wide price formation, but focuses on the marginal *differentiation* of prices due to mostly micro-scale attributes that are inherent in dwellings. It is not customary for applied hedonic studies to discuss the AMM model. However, in the present dissertation elements of the AMM model were implemented in the empirical hedonic specifications (for instance, distance to the city center). Article I assumes that both models are implementable via hedonic specifications. At coarser spatial scales, the hedonic attributes are assumed to become regional features, and, thus, the results communicate elements more applicable to the AMM model's scope. At more refined scales or at the completely disaggregated observation level, the hedonic attributes are properly referring to what hedonic price theory communicates. Aggregate results were understood as price differentiation factors inherent not to properties, but to the sub-regions of a city. The dissertation does not discuss the issues of the modifiable areal unit problem or of the precise theoretical integration of the AMM and hedonic model and their implementation via regression specifications, because such issues fall outside the thesis' scope.

One of the main characteristics of the dissertation in relation to the described tension between the AMM model and the hedonic theory is the empirical exploration of sufficiently complex spatial mechanisms in housing price formation and differentiation. This motivated the use of spatial hedonic analysis as the primary methodology and of the urban complexity tools of cellular automata and fractals as supporting methods. Each of these approaches has a sufficiently developed theoretical foundation and a clearly delineated niche—as is especially obvious in the case of hedonic studies—in which the empirical applications have been shown to provide solid results. The major part of the analysis conducted in the dissertation articles considered hedonic and complexity tools as complementary to each other, but nonetheless analytically independent. This allowed to fully exploit the merits of each approach and to apply it in detail, letting the complementary approach inform but not interfere. However, in certain instances, the need for a more comprehensive understanding of spatial behavior required a working at a more general level than each theory enables. This is apparent in article V and, to a lesser extent, in articles IV and I. In these cases, the unifying role is performed by a computational exploration of spatial interaction mechanisms. Such results cannot be easily placed within known urban economic theories. It is clear that a unified theoretical framework, especially pertaining to economic behavior across multiple scales, has not yet been fully developed in scientific literature. This dissertation's emphasis on computational approaches is in line with current cross-cutting work in the spatial and economic disciplines (Ioannides 2013; Batty 2007, 2013).

The analysis of price formation and differentiation mechanisms in articles I-III focused on the partial equilibrium of the housing market. Although the implemented regression models include controls that relate to other economic sectors, the inherent limitation of hedonic analysis is the absence of cross-sectoral flows and interactions. This represents an advantage as well as a disadvantage. On the merit side, hedonic analysis enabled the exploration of the inherent attributes of properties and their surrounding environment, which are important elements in adaptation and resilience studies. On the negative side, caution is needed in generalizing these submarket, subsector results and translating them into robust policy recommendations for the whole urban economy. Although the outcomes in articles I-III aim to provide empirically sound evidence about risks, amenities, and related policies in the housing market, the outcome will still rely on interactions with other sectors and related policies. For instance, the transport and energy sectors are key in adaptive capacity and have multiple links to land use dynamics and housing market behavior.

8. Synthesis: implications of the results for sustainable urban adaptation

The ability of urban agglomerations to generate wealth and, concurrently, to produce negative environmental externalities is a central issue in sustainable urban development. Understanding the costs, benefits, and tradeoffs of alternative spatial equilibria is therefore important for linking climate-proof with sustainable urban planning (Verhoef and Nijkamp 2002; Brooks et al. 2012; Barnett et al. 2015). In this context, the management of climate-sensitive ecological risks and amenities in spatial planning has to reconcile the mishap that spatial economic processes responsible for the minimization of urban ecosystem services (ES) also facilitate the success of cities. Given that climate change has rendered climate-proofing objectives necessary (as opposed to just desirable), the eventual aim of urban adaptation research is to understand the costs and tradeoffs of transitioning to spatial equilibria (cf. Rode 2013) that have both climate-proof and sustainable development character. In the context of the present dissertation research, this aim applies both to the partial equilibrium of the housing market and to important aspects of the land use equilibrium of a whole urban region. Key planning instruments in this respect are, among others, investment and regulation of time and space (Echenique 2015), which in practice concern both physical and behavioral interventions. This Section describes how the thesis' results address the abovementioned concerns and concludes with notes on the position of the results in the wider context of urbanism.

8.1. Contextualizing investment in ecological amenities while making ecological risks transparent

Regarding physical investment in green attributes to which the housing market reacts, the dissertation results suggest that the implementation of ES-generating land uses should be spatially contextualized if the triple goal of sustainability (i.e. harmonizing social, economic, and environmental objectives) is taken in earnest. It is evident that an adaptation strategy can misplace investments in ecological amenities in terms of the location, extent, and scale of costs and benefits.

The results draw a practical link between adaptation and hedonic amenities: it is evident that both climate-proofing tasks and housing market mechanisms are sensitive to the type of ecosystem in a particular location. With respect to climate-proofing, certain natural land uses carry specific ecosystem services and therefore solve particular types of problems. With respect to housing markets, prices react differently to different ecosystems and therefore the costs and benefits of implementing different natural land uses will vary. It, thus, appears that achieving both climate-proofing and economic development objectives (and, by extension, increased adaptive capacity and resilience) can be assisted by estimating the spatially heterogeneous impacts of green amenities over an urban area.

In addition to spatial heterogeneity in price effects, a further aspect of spatial behavior that is not frequently discussed is the need to address the horizontal diffusion of costs and benefits of green investments. More specifically, the spatial spillover marginal impacts of green amenities on housing prices are conditional to the subtype of the associated land use. Some land uses may contain the amenity benefits at the investment location while others may distribute them mostly to the surrounding areas, i.e. price effects can be mobile or immobile. These differences between the spatial effects of various land uses raise the question of who benefits from investments in certain land uses, showing that the welfare profile of an adaptation strategy is also dependent on the specific type of implemented land use. The issue is further complicated by the fact that addressing certain impacts requires specific land uses, since each land use has its specific ES profile and climate-proof function. In such a case, urban finance planning will need to tailor related capital investment/financing plans to a given green solution, rather than the other way around (cf. Blair 1995: 168-188, 274-303)

At the same time, the adaptive capacity of urban areas is hindered by the fact that urban housing markets contain imperfect information about the spatial distribution and level of climate-sensitive ecological risks (in this case, flooding). As a result, housing markets tend to overemphasize the benefit-dimension of natural features that contain both amenities and risks, while downplaying the risk dimension. In this respect, there are clear indications that investing in information—a behavioral regulation of space—can be effective in adaptation strategy. In the case of floods, public disclosure of risk maps induces price and demand adjustments so as to better reflect the spatial distribution and, in some cases, probability of risks. This shows that soft regulation, such as by the means of disseminating information, contributes to better informed—and thus—resilient, housing markets, and that markets are able to internalize new information rather quickly and accurately. Such information policies should also be ready to address the fact that the processing of risk information by markets might be bounded-rational, with an inaccurate correspondence of risk perception to factual threat, notably at the extremes of the probability spectrum.

The market adjustments to flood information imply that a combination of soft regulation of space (behavioral dimension) and investment in proper hazard mapping and information dissemination infrastructure (physical dimension) may work just as well as more disruptive planning instruments, such as zoning (physical regulation of space) or taxation (a more direct and contested behavioral policy). This conclusion can be applied also to other non-obvious climate-sensitive risks; for Finland, heat-related stress and sea-level changes. With the rise of ubiquitous and location-enabled information, it is clear that the effectiveness of information-based behavioral regulation of space has the potential to play an important role in spatial planning and the management of environmental risks. Their effectiveness, however, is still hindered by the inherent bounded rationality of the housing market when it comes to risk perception, indicating that a combination of information dissemination tools and traditional zoning may be the most effective for adaptation strategies.

8.2. Multiscale coordination in urban adaptation research and decision-making

As man-made systems and climate-related impacts become ever more complex, so does the need to better explore a greater number of levels and hierarchies of interaction than well-tested but simplifying models are able to account for (cf. Brueckner 2011). This complexity is spatial and temporal; in this dissertation's case, the manner in which housing prices fill urban space exhibits notable spatial and temporal differences when comparing micro-scales (for instance, city blocks or neighborhoods) to macro-scales (for instance, municipal subdivisions or postcode zones).

In the spatial continuum, a vertical hierarchy can be discerned in the entering of ecological amenities in the formation of housing prices. Their marginal effect will depend on the spatial unit in question, that is, one must specify whether an intervention and its marginal impact refers to individual properties, neighborhoods, or larger municipal divisions. Certain amenities enter price formation already at large municipal divisions, remaining relevant all the way down to neighborhoods and individual sites, while others enter price formation only at finer spatial scales. These variations suggest that, while the effects of risks, amenities, and related policies on housing prices are typically assumed homogenous across spatial scales, the granularity—and sometimes opposing dynamics—seen in the empirical data also needs to inform the design of effective spatial strategies.

In the temporal continuum, while a long-term equilibrium in the geographical configuration of prices is observed, annual variation is in evident disequilibrium, and the particular dynamics differ at each scale. This temporal complexity adds to spatial complexity and encourages the incorporation of equilibrium and dynamical models in one framework regardless of occasionally different underlying assumptions (cf. Simmonds et al. 2013). This may be important for successful adaptation strategies, since urban adaptation is increasingly confronted with the need to optimize multiscale spatiotemporal processes in addition to multiple objectives.

The observed spatiotemporal complexity, firstly, highlights an urban analysis issue. Some interventions are more relevant to the city-wide spatial equilibrium described in the AMM model. Other interventions are more relevant to the microscale mechanisms described by hedonic price theory. While the AMM and hedonic price approaches are built upon the same underlying microeconomic behavior, they start from different aggregation levels, and their connection merits better exploration in future research. It is necessary to investigate how the two approaches meet vertically. This will allow developing policy assessment tools that evaluate more accurately impacts across multiple bottom-up and top-down scales.

Secondly, from a policy perspective, the observed spatiotemporal complexity highlights an urban governance issue. The planning of certain ecosystems will require regional coordination across multiple scales, while the planning of others can be safely left to local developers or governing bodies. Developing policies with specific scales in mind will ensure that they do not hinder or are out-of-sync with benefit-generating mechanisms (compare to the discussion in Section 8.1). This is crucial, because urban adaptation involves physical and social processes that operate—but still interact—at different spatial scales.

8.3. Spatial planning and climate-sensitive risks and amenities in the urban region of Helsinki

The urban region of Helsinki has been analyzed in all dissertation articles (Pori and Rovaniemi were studied only in two of the articles). As a result, a set of recommendations can be drawn specifically for Helsinki's urban region. It is possible to generalize these recommendations, but only to cities with similar configurations of risks and amenities and with similar responses of their housing markets to those attributes.

Urban growth and the residential real estate market in Helsinki's region appears to place disproportional emphasis on amenities in relation to risks. For its coastal zone, this means that a tremendous amount of economic value is concentrated in flood risk areas, while the coastal housing market is not fully aware of the risks. Although the dissemination of flood risk information corrected, to some extent, this asymmetry, research literature as well as the performed simulations indicate that the effect will fade away and growth will continue to be disproportionally high in the coast. For inland areas, the asymmetry means a heightened rate of encroaching into available green spaces, especially forests, whereas the risks that this reduction of ecosystem entails are largely non-transparent by nature, since it is difficult to expect that indirect impacts that follow from reduced ES, such as heat-related stress, capitalize negatively in the housing market. Moreover, while the proximity of dwellings to the coast generates considerable economic value, the forecasted reduction of green spaces implies loss of economic value for most properties and the benefit only of the properties near protected green spaces and man-made parks.

These trends can be interpreted as an exacerbation of the spatially heterogeneous distribution of locational advantages and disadvantages. The dissertation results suggest a few concrete directions for the urban area's spatial policy. Firstly, it is suggested that natural land uses in areas near the city's center should be allocated specifically to a mix of urban forests and parks as this mix generates spatially extensive and diverse economic value via a combination of direct and spatial spillover channels. In Helsinki region's suburban periphery, the dissertation results suggest a preservation of the current mix of forests and agricultural land in order to achieve the generation of economic value of a similar nature as in central areas. Helsinki's urban region will also benefit from a continuous dissemination of risk and climate-proofing information, not only about floods, but for other non-transparent risks, too. Information policies need to place focus also on the connection between risks, land use options, and the state of the urban natural environment. It is evident that as ecological risks will become more transparent, identifiable, or perceptible, the capacity of the abovementioned green solutions to generate economic value will increase. It is thus important to suggest that imperfect information does not only concern risks, but also amenities. As has already been mentioned in this introduction, a permanent adjustment of the real estate market with respect to spatially explicit risks and amenities implies that the market is in a better position to cope with future climate-related shocks, because the increased information on risk and amenities will ensure that the market's resources are better distributed or focused in face of ecological and climate change impacts: i.e. better information leads to more resilient markets and society. The dissertation results suggest that Helsinki's urban region will greatly benefit from an increased coordination across the various levels of spatial planning and governance. This is mainly due to the fact that the discussed benefits require an increased sensitivity of the implementation to spatial and temporal scales – such tasks most often require the coordination of multiple governance levels.

Lastly, the dissertation results imply that Helsinki's adaptation profile will ultimately depend on its city-form policy. The presented spatial analyses suggest that the region needs a comprehensive study of the implications of alternative density and land use configurations. The results imply that a maintenance of agglomeration benefits and a stricter regulation of natural land uses is crucial for a thriving and climate-proofed Helsinki region. The physical boundary of urban growth in Helsinki's urban region is constrained by administrative borders. The demand for housing is constantly rising, especially compared to surrounding regions, while the loss of green infrastructure implies notable loss of economic value. All these factors suggest the goal of maintaining agglomeration benefits necessitates a dense city. Intensifying development morphology in Helsinki is supported by other studies as well (e.g. Loikkanen and Laakso 2016). It should be noted, however, that the exact parameters of density targets need to be further explored; the region is in need of multi-sectoral, spatially disaggregated modelling in order to identify truly optimized recommendations about city form and land use configuration.

8.4. Transitioning to climate-proof sustainable cities

It was stated in earlier Sections that the process of urban adaptation not only deals with threats, but also represents opportunities. This thesis shows that an urban adaptation strategy that, on one hand, targets a built environment that is heavily invested with urban green while concurrently maintaining agglomeration benefits and, on the other hand, ensures the transparency of ecological risks will reinforce urban economic productivity while enhancing the resilience to climate-sensitive impacts. When in the proper spatial context, ecological benefits do not conflict with agglomeration benefits, provided that risks are transparent. These targets can rely on a combination of physical investment in ES-rich land uses and an information-led regulation of risky areas. Thus, a recommendation for *green and sufficiently agglomerated settlements, with increased information flows about ecological risks, and spatially parameterized implementation of ecological amenities* is made. When physical boundaries constrain urban growth, it can be assumed that this recommendation implies increased densities in order to maintain adequate allocation of space to green infrastructure.

The indications that the climate-proofing capacity of green spaces—if those spaces are properly implemented—can be combined with the generation of economic benefits imply that transitioning to a more sustainable spatial equilibrium in the housing market might not be so costly after all, although more research is needed to understand the full array of costs and benefits. In addition, the urban development simulations show that a transitional pathway to a more sustainable equilibrium does not necessarily have to be disruptive for urban growth and urban morphology. Small variations in the spatial distribution and intensity of growth constraints are capable of producing measurable changes in urbanization trends. These changes are not radical shifts in urban dynamics, but deviations in existing dynamics that result in measurable differences in land use morphology within a few decades. This observation, in combination with the discussion in Sections 8.1 and 8.2, supports the idea that targeted changes rather than big ones can facilitate gentle transitions to climate-proof and sustainable spatial equilibria.

In aiding assessments for alternative urban adaptation strategies, the dissertation results may form the basis for a set of guiding questions about harmonizing ecological and economic effects. These questions may be used as a guidance by adaptation experts and environmental planners when their task is designing and implementing a strategy that harmonizes the benefits of climate-proofing interventions with agglomeration benefits and minimizes the risks of climate-sensitive hazards.

Divided into six categories, these questions are:

Type	What type of ecosystem is involved in an intervention?
Location	Where in the urban area is the intervention located?
Scale	What is the size of the intervention and target area?
Diffusion	What is the spatial reach of the economic effects?
Information	Are both climate-sensitive risks and amenities transparent?
Evolution	How are neighborhood and city-wide trends affected?

It must be emphasized that these questions are not stand-alone; they are questions *about* ecological and economic effects. While they may appear trivial at first sight, they raise issues upon which the effectiveness of a strategy relies. These questions have been too frequently omitted in technical assessments or the drafting of urban visions, resulting in the perpetuation of unnecessary tensions between ecological and economic objectives.

9. Afterthoughts: Future directions and relating the results to visions of future cities

Based on the experiences gained and the knowledge produced in this dissertation, and while the research can be continued along several pathways, the most urgent actions needed in the future are the following. Firstly, the temporal volatility of the implicit prices of ecological amenities and risks needs to be explored, in conjunction with achieving a better understanding of agents' decision behavior in the housing market. Secondly, the cross-sectoral distribution of environmental impacts and of alternative spatial policies aimed at addressing those impacts has to be explored in an encompassing manner. Thirdly, both analytical studies and strategy development are in dire need of expanding the historical timeframe. Informing the future development of urban societies when important parameters are in flux (demographics, climate, ecosystems, and technology) can benefit from analyzing similar occurrences in the past. This long-term information can be supplied by the paleo-environmental and archeological records, but is not captured by economic datasets.

The first direction will need an amendment of hedonic price theory by introducing more elements of bounded rationality than currently included. This task also suggests that the value-based rationale implied by hedonic theory will need to be complemented by non-utilitarian decision-making theories. The second direction will need the implementation of multi-sectoral spatially disaggregate urban simulation models, with elements of both equilibrium-based microeconomic theory and disequilibrium-based complexity theory. The third direction implies work in extending social and economic data to match their paleo-environmental counterparts, while refining the theories available to us in explaining the co-evolution of human societies, ecosystems, and climate. All three directions will contribute toward the same goal: a fuller understanding of human-environment interactions in urban regions under changing boundary conditions.

Returning to urbanism, many technical problems related to climate-proof sustainable urban planning will call for non-technical solutions (cf. Hardin 1968), or at least an earnest consideration of non-technical dimensions. One can be certain that thinking about cities, climate change, and climate-related urban strategies will raise debates of a more general nature about future cities. Urban research has been long characterized by a divide between technology and policy (Batty 2004) or efficiency and equity (Brooks et al. 2012). This raises the question of the position of technical quantitative analysis, such as in this dissertation, in the wider context of thinking about cities, especially since visions of good cities are value-dependent and change within and across cultures.

Technical, that is to say, merely engineering approaches are but one element of city design, alongside with non-technical (such as aesthetical and ethical) approaches. Technical research is primarily concerned with the needs of the city, while non-technical research extents to the realm of desires and values. Both spheres have to be taken into consideration when designing strategies for the future development of cities, if such cities are to truly support wellbeing. An improper understanding of the role of technical urban research may distort the urban visions of future generations. In the past, such flaws as overemphasizing the rational-technical aspect of planning led to the appearance of phenomena like the plans of Brodsky and Utkin (Nesbitt et al. 2015). These plans sprang as a reaction to enforcing rational planning principles as the sole guidance for planning and design. The subdued creativity was rechanneled into imagining bizarre cityscapes, which began as mere thought experiments but currently seem to inspire the present generation to realize these irrational city plans in practice, producing actual city projects. This tendency may lead to the appearance of distorted cities that border the irrational; a cunning revenge of the irrational.

A better approach to utilizing technical research is to communicate it with value-driven viewpoints. Therefore, it is advised that the recommendations based on the results of this dissertation research are placed within the boarder context of urbanism. These recommendations are technocratic in nature; they are tools of achieving value-loaded visions of cities, but themselves do not suggest such visions. The results of the research are applied to currently existing models of cities, and cannot answer such questions as whether radically different modes of human settlement can be equally productive. Whether or not the polar opposite blueprints of LeCorbusier (dense towerscapes) and Frank Lloyd Wright (scattered individual settlements) may be equally sustainable, depends on the production, communication, and perception of particular urban spaces, which has been shown to rely not only on denotative (for instance, technical, functional, utilitarian, and need-based), but also on connotative (for instance, cultural, symbolic, and want-based) codes (Eco 1972, 1986; Gottdiener and Lagopoulos 1986; Lagopoulos 2005). These codes are vernacular and a large portion of them have certainly the capacity to create market forces and in the end influence the more technical aspects of an urban system (Toivonen and Viitanen 2015, 2016). What rational analysis can do is to assess the implications of alternative visions of good cities in their contexts, so that the inherent creativity, adaptability, and resilience of humans is facilitated.

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Available as an MPRA working paper

Ecosystems and the spatial morphology of urban residential property value: a multi-scale examination in Finland

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Ecosystems and the spatial morphology of urban residential property value: a multi-scale examination in Finland

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This paper provides evidence for the spatial effects of ecosystems on the formation and differentiation of urban housing prices. The study estimates spatial hedonic functions on data from the Finnish cities of Helsinki, Espoo and Pori in order to understand the behavior of natural land uses as hedonic attributes from citywide to micro spatial scales. The results indicate that ecosystems enter consistently the hedonic function as spatial scales progress; a certain hierarchical logic can also be discerned in the appearance of new attributes from one spatial scale to another. Vertical variation across spatial scales is complemented by two horizontal forms of distance decay in each scale: a logarithmic decay of per m^2 capitalization of some amenities when moving away from the source, and a linear dependence of the implicit price of other amenities on distance to the city center. Lastly, the marginal values exhibit notable temporal variation, even after using de-trended prices. The results highlight the structural, or consistent, role of ecosystems in the housing market and suggest that the valuation of ecosystem services depends on the spatiotemporal context, that is, the housing market is selective about these services.

Keywords: urban ecosystems, spatial effects, residential property value

1 Introduction

A meaningful incorporation of the ecosystem and its services in urban adaptation and sustainability analysis must consider the details of its role in urban welfare. To this end, the differentiation of residential property value is an important indicator because it largely reflects the morphology of urbanization benefits for residents. Linking the ecosystem to property prices is thus one way to understand its structural role in an urbanized setting. De Groot et al (2002) and Bateman et al (2010) provide an enumeration of methodologies for linking the ecosystem to economic value, with the hedonic approach being the most relevant for the housing market. In hedonic price theory, housing is viewed as a composite commodity that consists of a bundle of *n* attributes. This modifies the housing buyer's traditional utility function from $\mathrm{u}(c,q)$ to $\mathrm{u}(c,a_1,a_2,\dots,a_n)$, with a_i an element of the dwelling's attribute bundle, q housing consumption and c the sustenance or "bread" consumption (Brueckner, 2011, p.117). By estimating the market price of this commodity as a function of its attributes, it is possible to derive an implicit marginal value for each of the attributes (e.g. Rosen, 1978; Dubin, 1988; Sheppard, 1999).[1]

The aim of this study is to analyse the structural role of ecosystems in residential property value formation and differentiation at multiple spatial scales, while controlling for other important factors. The study estimates the marginal effects of selected ecosystems on property value through hedonic functions. However, the hedonic viewpoint contains key uncertainties with respect to what price differentiation mechanisms are reflected by the estimated marginal values. This article suggests that a city-wide spatial equilibrium and micro-scale demand and supply must be considered concurrently when assessing the effects of ecosystems, and this implies the use of multiple spatial scales. For this reason, an amenity-based residential location theory (Brueckner et al, 1999) is utilized as a necessary theoretical amendment to the empirical merits of hedonic price theory. The text will refer to the former

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[1] The estimated coefficients are interpreted as marginal values or effects. They can be further treated as functions of household characteristics, retrieving the demand for amenities (Brueckner, 2011, pp.117-118; Quigley, 1982). Household characteristics are important also for the main alternative of hedonic regressions, the discrete choice modelling of residential location (e.g. McFadden, 1977; Ellikson, 1981; Cropper et al, 1993; Sheppard, 1999); such data were not available in this study.

as the citywide mechanism or equilibrium and to the latter as the micro-scale mechanism of fragmentation or differentiation of value.

The spatial equilibrium of residential location and the resulting value differentiation across the city (von Thünen, 1826; Alonso, 1964; Mills, 1967; Muth, 1969) on one side, and the local mechanism of micro-scale demand and supply that results to further value fragmentation on the other side, are two distinct price differentiation mechanisms. Considering the broader urban economic system, these mechanisms are concurrently reflected by the implicit values of man-made or natural elements in the built environment, if observed market prices are used for the estimation of those values. Moreover, the valuated flow of ecosystem services suggested in environmental economics literature is in fact a spatial flow, since the urban economy is essentially a spatial game of finite resources and land use competition. Not accounting for these details hinders the correct assessment of the impacts of ecological change or its use as an adaptation and sustainability tool in the city. The present study has employed the amenity-based residential location theory of Brueckner et al (1999) that, together with hedonic price theory, establishes theoretical expectations for the structural role of the ecosystem in the differentiation of property value.

The next section proposes the implications that follow from the consideration of an amenity-based location model in conjunction with hedonic theory with respect to the role of the ecosystem in value differentiation. Section three outlines the empirical methods and data used in the study. Section four provides empirical results and a discussion in support of the theoretical propositions of the first and second sections. The fifth section offers concluding remarks about the studied spatial effects. In addition, the conclusion links the presented research to a broader context of urban adaptation and sustainability.

2 Amenities as a structural element in value differentiation

Hedonic price theory captures well aggregate supply and demand in the property market but does not account for the idiosyncrasies of each city or other value formation mechanisms that might be operating concurrently. Although comprehensive econometric procedures are suggested for arriving at the best hedonic function specification (e.g. Sheppard, 1999, pp.1613-1619; LeSage and Pace, 2009, pp.155-187), this in a sense turns the procedure on its head, overlooking the merits of theoretical urban modelling. The Alonso-Mills-Muth family of models does place theoretical expectations for the morphology of value in the city, but is best used to describe the North American monocentric city of the past centuries. To this end, the location model of Brueckner et al (1999) has two advantages. Firstly, it is especially fit for the Nordic urban morphology from which this study takes its empirical evidence. Secondly, it considers the spatial morphology of amenities as the main determinant of the spatial equilibrium, with the ecosystem being one of the three accounted amenity types. This enables to first lay out theoretical expectations for the structural role of the ecosystem on price formation that complements the numerical merits of the hedonic approach.

Natural and historical amenities are assumed exogenous to the bid-rent function, while modern cultural amenities are seen as endogenous consequents in locations where wealthy households locate. Dwelling consumers are characterized by the utility function $\mathrm{u}(y - tx - pq, q, a)$, where y is income, t commuting cost, x distance from the central business district (CBD), p price per housing unit, q housing consumption and a amenities. Variables p and q are functions of x, so that $p(x)$ is a "bid-price" function with two important components: the t/q ratio of the Alonso-Mills-Muth models plus an amenity-dependent component. The rate of change $\mathrm{d}p/\mathrm{d}x$ is the function $p'(x) = -[t/q(x)] + [\{v^{\mathrm{a}}[y - tx, p(x), a(x)]\}/q(x)]a'(x)$, where v^{a} is the marginal valuation of amenities after optimal adjustment of housing consumption. As Brueckner et al. note, most models unjustly assume $v^{\mathrm{a}} \equiv 0$ and overemphasize the role of $t/q(x)$ (1999, p.96). In addition, evidence is cited from Wheaton (1977) that $t/q(x)$ does not vary sufficiently across cities to justify its frequent use as the crucial location determinant (1999, p.93). The second constituent of $p'(x)$ is an important proposition when trying to understand possible mechanisms by which the environment forms and differentiates real estate values, especially in light of the major ecological and climate changes the cities have to adapt to. The environment is internalized as a structural element of the urban system. From this point on, the key assumptions are that the marginal valuation of amenities rises sharply with income, and that the wealthy are characterized by a high opportunity cost of time (Brueckner et al, 1999, pp. 93, 96).

While insignificant variation in amenities across the city makes the location of the wealthy dependent mainly on transportation cost and dwelling type preferences, introducing a realistic spatial variation in exogenous amenities produces value morphologies that are consistent with many European cities. The wealthy will outbid the rest in the city centre, if it contains a sufficiently maintained historical built environment and "unique" natural amenities that stand out in the overall distribution of nature across the city. Urban blue in the form of a coastline or attractive river banks are such cases. Moreover, even in a homogenous distribution of green across the city, it is reasonable to assume that urban green spaces at the centre will have an exogenous effect on location. Firstly, they are oftentimes combined with historical amenities (e.g. a park next to a museum) or are valued design elements themselves (e.g. through their architectural details). Secondly—and more pragmatically—they alleviate negative externalities such as air, noise and visual pollution, making the otherwise beneficial central locations more favourable (e.g. Givoni, 1998; Tyrväinen, 1997; Tyrväinen and Miettinen, 2000; Hauru et al, 2012).

Modern amenities as endogenous factors suggest that contemporary amenities such as restaurants, cinemas and shopping or art districts tend to follow high concentrations of wealthy dwellers. This establishes a certain neighbourhood spirit, culture or prestige. The most obvious effect of this tendency is that it reinforces the location pattern described in the previous paragraph; that is, historical and natural amenities in the city centre will attract the wealthy and this will further establish modern amenities in a positive loop-like feedback. An equally interesting effect of endogenous amenities stems from the fact that there will always be indeterminacy in additional favourable locations for the wealthy, beyond the obvious city centre. The value of such minor cores will be then reinforced by the emergence of modern amenities, inducing a multicentric morphology of high-value clusters.

It is reasonable to assume that the theorized location equilibrium will be mirrored by an empirically observed morphology of residential values; the aggregate demand of the wealthy for a particular location will drive its average value up. As already mentioned, this general price differentiation is followed by a subsequent fragmentation due to quality variation on a dwelling and/or small neighbourhood basis; this is well explained by hedonic price theory. Urban ecosystems naturally enter both differentiation layers, and this means that hedonic functions will estimate non-constant implicit values that reflect both city-wide and micro-scale mechanisms. Thus, the following theoretical expectations can be put forth:

Firstly, a varying spatial aggregation scheme will separate the two differentiation mechanisms: aggregate ("coarse") scales will reflect what ecosystem aspects are relevant to the overall spatial equilibrium, whereas disaggregate estimations will indicate those additional aspects that are responsible for the micro-scale fragmentation of value. Secondly, since the marginal valuation of amenities is a function of location, the estimated hedonic functions are expected to reflect this feature. The implicit value of amenity a_i will be non-constant, dependent on and variable with location. Thirdly, spatially weighted measures of price per unit of housing consumption are likely to have strong empirical relevance, as they are good proxies for the endogenous component of the utilized amenity theory.

3 Data and methods

The analysis has used property transaction data from Helsinki, Espoo and Pori. Helsinki (≈ 535,384 inhabitants as of 31.12.2011, 21,655 hectares) is the capital of Finland and Espoo (≈ 252,439 inhabitants, 33,219 ha) is one of its adjoining municipalities. Both cities are part of the broader capital region at the southern tip of Finland, on the coast of the Baltic Sea, with a population size of about 1,360,000. Pori (≈ 83,133 inhabitants, 88,135 ha) is a river town in the southwest of Finland. In terms of population rank size, Helsinki and Espoo hold the 1st and 2nd ranks, while Pori the 11th (Statistics Finland, 2013).

The transaction data record the selling price, debt component[2] and technical maintenance cost of the dwelling, together with its postal address and several structural characteristics of the property.[3] All monetary variables (price, debt, maintenance cost) were adjusted for inflation with 2011 as the reference year. The original data were enhanced in two ways. Firstly, based on their postal address and a geo-referencing operation, the geographical coordinates of the observations were retrieved in order to enable spatial analysis. Secondly, several ecological variables were added to the original observations in order to produce what Dubin (1988) describes as the structural, locational and neighbourhood characteristics of the dwelling, suitable for the estimation of hedonic functions. The final selection of variables is presented in Table 1. For the cases of Helsinki and Espoo, CBD refers to the central business district of Helsinki.

TABLE 1: THE VARIABLES OF THE ANALYSIS

Variable	Description	Unit
PRICE	Selling price per m^2, adjusted for inflation (ref. year 2011)	€ thousand per m^2
LAMBDA	Spatial error coefficient (λ)	€ thousand per m^2
DEBT	Debt of the housing committee for large repairs, adjusted for inflation	€ thousand per m^2
MAINT	Technical maintenance cost, adjusted for inflation	€ thousand per m^2
FLOORSP	Floor-space	m^2
ROOMS	Rooms, excluding kitchen	multinomial (1–9)
FLOOR	The floor on which the apartment property is situated	multinomial (1–9)
AGE	Difference between selling and construction year	years
BADCND	Bad condition	binomial (1/0)
AVGCND	Average condition	binomial (1/0)
CBD	Distance to Helsinki's central business district	metres
SEA	Distance to the coastline	metres
LAKE	Distance to the nearest lake	metres
LAKEVIC	In the immediate vicinity of a lake (radius varies slightly by sample)	binomial (1/0)
RIVER	Distance to the river bank	metres
PARK	Distance to the nearest park	metres
FOREST	Distance to the nearest forested area	metres
PCTFORE	Portion of grid cell that is forested	%
SPREC	Distance to the nearest sports/recreation area	metres
PARKDENS	Park density	facilities per km^2
SPRECDENS	Sports/recreation areas density	facilities per km^2
OWNPLOT	Whether the property has a privately owned plot	binomial (1/0)
ONSALE	Amount of time that the property was on sale in the market	days
YEAR	Transaction year dummy; 0 is assigned to the earliest year	bi- or multinomial
DWELTP	Dwelling type (1: apartment, 2: row house, 3: single family house)	multinomial (1–3)

[2] Debt arises mostly in units under a common roof, *e.g.* the units of an apartment building or row houses under a common roof. Such properties frequently establish a managing committee. Large maintenance expenses such as the replacement of the roof are undertaken by the committee and financed by a loan. The loan is then distributed to each property, usually according to its size, and the debt component of a property reflects this obligation. It bounds the property rather than the owner, and passes from one owner to the next when the property is sold.

[3] These data are voluntarily collected by a consortium of Finnish real estate brokers and the dataset is maintained by the Technical Research Institute of Finland (VTT). As not all real estate agencies participate, the dataset represents a sample (albeit rather large) of the total volume of transactions.

The discussion in the preceding sections motivates a spatial approach. Hedonic functions were repeatedly estimated for neighbourhood-level (grids of spatially aggregated observations) and dwelling-level (disaggregate) data. The neighbourhood-level data were produced by aggregating the observations into four separate hexagonal lattices with diameters of 5778, 2207, 521 and 199 metres. The dwelling-level data refer to the original observation points and did not involve a spatial aggregation scheme. The four non-rounded dimensions of the hexagons represent non-successive points selected from an exponential spatial scale sampling scheme ($scale_{n+1} = scale_n * e^{0.4812}$), aimed at grasping how price forms at different spatial scales, from the city-wide level down to the local micro-scale. Aggregate observations contain transactions of all housing types (i.e. apartments, row houses, single family dwellings) for the period between 2000 and 2011. Disaggregate observations represent apartments only, and were split in annual or biannual subsamples to maintain an adequate sample size. Regardless of the aggregation scheme, the unit of the dependent variable and estimated marginal effects remains the price per square metre for one property; at the disaggregate level it reflects the value of each property, whereas at the aggregate levels it refers to the average expected value of a property belonging to a grid cell. The multiple aggregations should not be confused with the modifiable areal unit problem or the ecological fallacy issue (Viegas et al, 2009; Anselin, 2002). The aggregations are based on point observations and inferences made refer to the corresponding spatial units of neighbourhoods and city districts. Similarly, inferences about individual properties are based on disaggregate property transactions.

Explicit assumptions about spatial interaction were made, by letting the first-order von Neumann neighbourhood determine the construction of spatial weights. For a hexagon, this translates to its first ring of neighbours. For the disaggregate data, the Thiessen polygons of the points were used to extract contiguity. Spatial autoregressive models (SAR) were used, which implies that any identified spatial externalities are global (Anselin, 2003). However, the particular nature of the externalities has been data-driven. The general SAR function $\boldsymbol{y} = \rho \mathbf{W}\boldsymbol{y} + \beta \mathbf{X} + \lambda \mathbf{W}\boldsymbol{u} + \boldsymbol{e}$ (1) was assumed, where $\boldsymbol{y}$ is PRICE, $\mathbf{W}$ a spatial weights matrix, $\mathbf{W}\boldsymbol{y}$ a spatially lagged form of PRICE, $\mathbf{X}$ a matrix of independent variables, $\mathbf{W}\boldsymbol{u}$ a spatially autocorrelated error term isolating unobservable spatial effects, $\boldsymbol{e}$ an i.i.d. error term, and ρ, β, λ coefficients. Lagrange Multiplier (LM) tests in a maximum likelihood framework were used for simplifying (1) and resulted in all cases in the spatial error specification of the form $\boldsymbol{y} = \beta \mathbf{X} + \lambda \mathbf{W}\boldsymbol{u} + \boldsymbol{e}$. The foundations of these models are outlined, among others, in Anselin (1988), Anselin (2003), LeSage and Pace (2009), Anselin et al (2010), Piras (2010) and Gerkman (2011). The analysis has used the *spdep* module (Bivand et al, 2012) of R statistical software (R core team, 2012) and GeoDa spatial data analysis software (Anselin et al, 2005).

4 Empirical results and discussion

The first expectation set forth in the second section is that a multiple spatial aggregation framework will be able to detect the ecosystem's separate contributions to city-wide and micro-scale price differentiation mechanisms. Table 2 provides the hedonic estimations across different spatial scales for the Helsinki-Espoo urban area, and Figure 1 shows the discussed scaling structure.

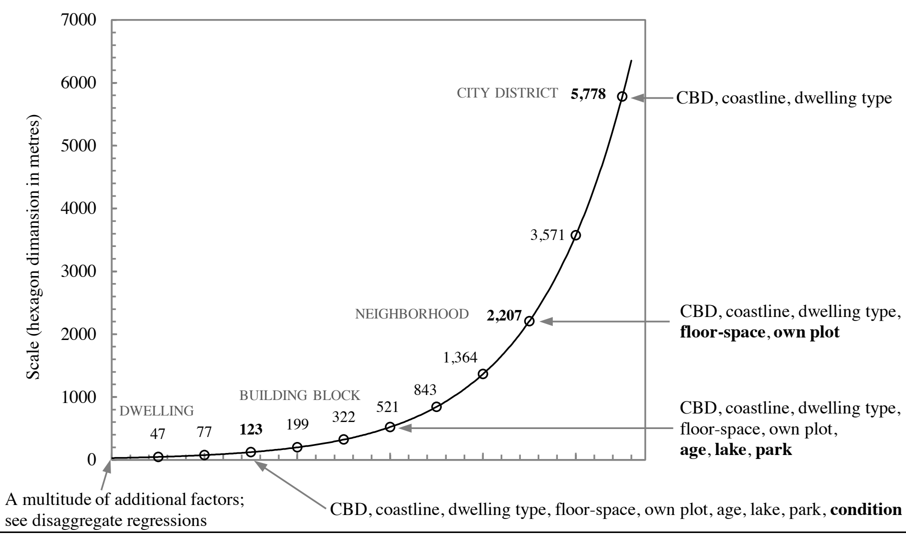
A structure of price differentiation factors is evident with respect to whether the price formation is examined via a few large districts or many small neighbourhoods. At the coarser spatial scale (5778 metres), 82 per cent of price variation is explained by proximity to the CBD and the coastline, and by the type of dwelling. As the scale becomes finer, additional factors—including additional ecosystems—enter the price differentiation process, while the unexplained variation increases. Most notably, while the coastline remains a strong determinant of price formation, a number of urban green and blue elements enter the differentiation process at relatively fine scales, starting at the 521-metre neighbourhood. The dominance of the CBD and coastline across spatial scales indicates their role as city-wide residential location determinants, in line with the theoretical expectation of Brueckner et al. (1999). Thus, the coastline can be considered as the most important environmental amenity for the Helsinki-Espoo urban area, whereas Helsinki's CBD (a historical district with a rich portfolio of architecture, urban design and green spaces) fits well in the role of historical amenity; the two fulfil the range of exogenous determinants anticipated by the utilized amenity theory.

TABLE 2: HEDONIC ESTIMATIONS ACROSS AGGREGATE SCALES, HELSINKI-ESPOO URBAN AREA

Scale:	5778m		2207m		521m		199m	
	Coef.	Sig.	Coef.	Sig.	Coef.	Sig.	Coef.	Sig.
Intercept	11.096	.000	9.767	.000	10.216	.000	10.633	.000
log [CBD]	–.859	.000	– .736	.000	– .665	.000	– .719	.000
log [SEA]	–.198	.000	– .313	.000	– .235	.000	– .212	.000
DWELTP	.657	.000	.665	.000	.471	.000	.368	.000
FLOORSP			– .003	.022	– .004	.000	– .004	.000
OWNPLOT			.647	.000	.405	.000	.289	.000
YEAR			.115	.000	.070	.000	.088	.000
LAMBDA (λ)			.339	.009	.466	.000	.448	.000
AGE					– .015	.000	– .015	.000
$[AGE]^2$					1.649e-04	.000	1.66e-04	.000
LAKE					– 9.022e-05	.003	– 6.419e-05	.001
log [PARK]					– .019	.003	– .033	.013
BADCND							– .235	.000
AVGCND							– .223	.000
PCTFORE							– .087	.063
PARKDENS							– .022	.135
SPRECDENS							– .005	.003
Adjusted R^2	.82		–		–		–	
Negelkerke R^2	–		.7		.67		.63	
N (of hexagons)	29		136		1149		3788	
Model type	OLS		Spatial error		Spatial error		Spatial error	

Notes: 1. The reported coefficients are interpreted as marginal effects and correspond to € thousand per m^2. 2. The observations (hexagons) are not a sample but artificial city regions that physically exhaust space.

FIGURE 1: PRICE DIFFERENTIATION FACTORS IN THE COMBINED HELSINKI-ESPOO AREA



Note: New factors at each scale shown in bold; scale ε increases exponentially: $\varepsilon_{n+1} = \varepsilon_n * e^{0.4812}$.

Regressions for the city of Pori yielded a comparable but more ambiguous hierarchy. The CBD dominates across scales together with the age and condition of the housing stock. Ecosystems become relevant at the 521-metre scale, represented by lakes and forested areas. The river's influence is clear only at 199 metres, while the coastline only at 2207 metres. Compared to the Helsinki-Espoo area, these differences may be partly due to a rather uniform spatial distribution of ecological amenities, in combination with the city's small size that limits serious negative externalities inside the CBD. Both aspects render the ecosystem relevant only in micro-scale differentiation, confirmed by the disaggregate estimations for Pori.

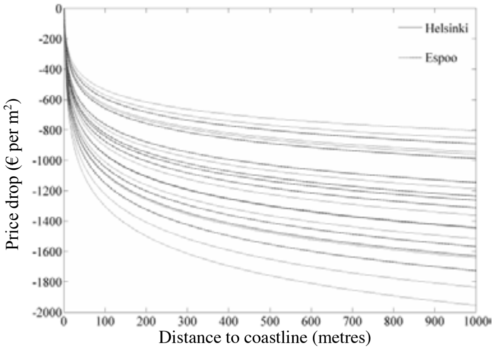
The estimations at the disaggregate scale have been able to confirm the assumed micro-scale differentiation mechanism. Tables 3a, 3b and 3c report the hedonic estimations for a large sample of apartments in Helsinki, Espoo and Pori between 2000 and 2011. As expected, property-specific attributes become evident differentiation factors at this scale, which contrasts to the dominance of neighbourhood-relevant factors in the aggregate models. However, it is important to notice that the city-wide factors are present at this scale as well, since the two price differentiation mechanisms co-differentiate value. A few price differentiation factors are common regardless of the city, most notably the distance of a property to the CBD and age- or condition-related attributes. Ecosystems appear as universally important in the price differentiation process, contrary to the conventional intuition that the influence of ecosystems is too weak to be detected.

Nevertheless, the kind of ecosystem detectable in price formation varies significantly between the three cities. Diversity is observed also in the functional form of the marginal effects. This naturally depends on what is available in each urban area and how it is incorporated in the built environment, but there is also evidence that residents are selective with respect to what type of ecosystem services they favour. The most vivid evidence for this is the fact that while it has been possible to model the marginal effect of urban green in all three cities, the mix of specific kinds of urban green—therefore, the mix of received ecosystem services—is different for each city. Another evidence for the selectivity towards the mix of preferred ecosystem services is the term FORES50*RIVER in the case of Pori; it indicates that proximity to the river bank increases price, but only for properties within 50 metres from a forested area. In other words, it is a specific mix of ecosystem services that influences value formation, a fact that casts doubt to the usefulness of dissecting ecosystem services beyond a certain limit, as they most often work together in complex ecological land use patches.

The logarithmic distance decay suggests that the positive effect of some ecosystems on residential property value concerns the dwellings in close proximity to the ecosystem. The marginal effect falls sharply when moving away from the ecosystem. Moreover, explorative spatial autocorrelation analysis (Moran, 1950) suggests that the price premium spills over to the properties that are neighbouring those in direct proximity to the ecosystem in question. Thus, the logarithmic distance decay likely encapsulates both pure and spill-over effects. For the case of Espoo and Helsinki, the coastline is the major ecosystem exhibiting logarithmic distance decay of marginal effects (log [SEA]). Figure 2a demonstrates this behaviour by plotting the estimated price drops in Espoo and Helsinki when moving away from the coastline. The strongest logarithmic decay is exhibited by proximity to the CBD.

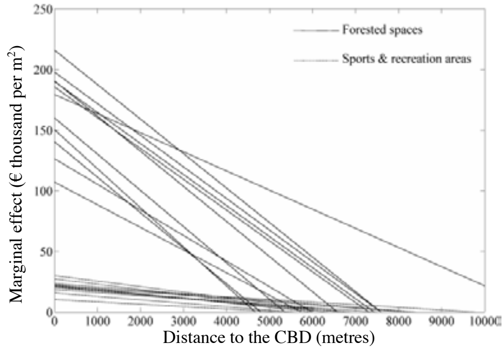
On the other hand, the interaction terms CBD*FOREST and CBD*SPRECDENS in the case of Helsinki's apartments suggest that other ecosystem services exhibit a maximum marginal value at the CBD, with the effect decaying when moving away from that location and its attributes. This distance decay has been detected in the marginal effect of forested and sports/recreation areas; it is indeed realistic to expect that the maximum marginal value of green is downtown where it is more scarce and—as mentioned in the second section—where it alleviates the negative externalities of the otherwise beneficial centre of urbanization and agglomeration. Formally, this can be expressed as *effect* = $effect_{max}$ – [*decay rate*]**CBD*, with the decay rate varying from year to year. Figure 2b shows the calculated distance decay for the marginal value of forested and sports/recreation areas in Helsinki for each year between 2000 and 2011. The rate of decay varies from year to year, which might be due to the way the broader economic and political forces influence the marginal values, as discussed later on.

FIGURE 2A: PRICE DROP WITH DECREASED PROXIMITY TO THE COASTLINE IN HELSINKI AND ESPOO



Notes:
1. The displayed effect refers to the rapid drop of the expected price per square metre due to moving farther from the Espoo-Helsinki coastline. All other hedonic attributes are assumed constant.
2. Multiple lines refer to multiple years in the 2000-11 period.

FIGURE 2B: DISTANCE DECAY OF THE MARGINAL VALUE OF TWO URBAN GREEN TYPES IN HELSINKI



Notes:
1. The efect of forested areas refers to 100 metres closer.
2. The effect of sports and reretation areas refers to one additional such area per one square kilometre.
3. The figure assumes all other hedonic attributes constant.
4. Multiple lines refer to mulyiple years in the 2000-11 period.

The third theoretical proposition has been that spatially weighted measures of price per unit of housing consumption will illuminate the endogenous component of the residential location model. The measure that has captured this effect is the λ (LAMBDA) coefficient, which is the regression coefficient of a spatially autocorrelated error component. Its use (and thus the use of spatial error models) was supported in the sample by LM tests. This component is not a random residual, but isolates (that is, cleans the dependent variable from; ref. Anselin, 2003) an unobserved neighbourhood effect on the price of a property in the same units as the property value (euro thousand per square metre in the present case). It is usually interpreted as the effect of difficult to operationalize factors, such as the culture or perception of an area, and is thus a potentially good proxy for the modern endogenous amenities that reinforce the high value of a neighbourhood. It is a global spatial externality, which suggests that the unobserved spatial effect concerns all observations but its impact is rather local and decays smoothly in progressively larger rings of neighbours, in the form of $\lambda\mathbf{WX}$, $\lambda^2\mathbf{W}^2\mathbf{X}^2, \ldots, \lambda^n\mathbf{W}^n\mathbf{X}^n$ (Anselin 2003, pp.155-159). Identifying the exact location where this effect is at its strongest needs further analysis and the employment of local (e.g. moving average) models. An alternative measure would have been the ρ (rho) coefficient, which is the regression coefficient of the spatially lagged version of the property value itself. The LM tests have not supported its use (and by extension the use of a spatial lag model) in place of the spatial error component, although exploratory regressions have indicated that the ρ and λ coefficients are numerically similar in the studied sample and both statistically significant.

The abovementioned elements can be interpreted as evidence that the price differentiation mechanism contains a positive feedback element that is akin to what Brueckner et al (1999) imply when describing modern endogenous amenities. Due to the nature of lambda as an unobserved small neighbourhood effect (Ahlgren and Gerkman, 2010; Anselin, 2003; Dubin, 1988; Sedgley et al, 2008; Wilhemsson, 2002), its use as a proxy for modern endogenous amenities makes more sense versus a more narrow interpretation that would see only the price level of a neighbourhood influencing a specific property's price. In other words, a more general endogeneity exists, which most likely does contain the price level of the neighbourhood, but this is intertwined with other difficult-to-grasp factors. The LM tests support this as well, by indicating that while both λ and ρ can be used, it is the former that exhibits the highest significance. A less strict treatment of endogenous amenities is also supported by considering that positive feedback and indeterminacy connected to rather diverse factors are known generators of form, pattern and growth in the city, rather than singular factors such as price; see Batty (2007; 1997) for computational expositions.

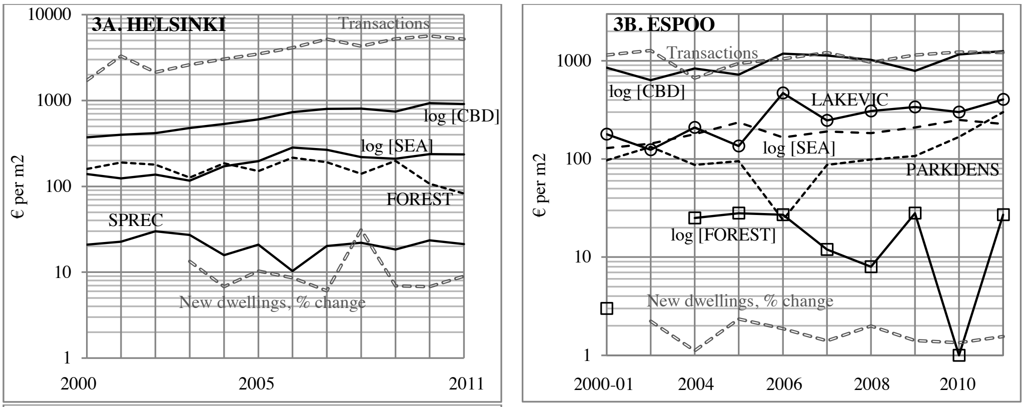
Another interesting element concerns the inter-scale behaviour of λ. Its strong presence across all scales, starting from the 2007-metre hexagons through to the disaggregate level, suggests that the endogenous amenity determinant of value is active both at the citywide and the micro-scale value differentiation mechanism. However, it has a noticeably higher magnitude at the disaggregate level, suggesting that while it participates in the formation of value morphology—or zones—across the city area, it intensifies when further refining values within the already formed zones. Nevertheless, this is potentially misleading as it is known that the value of lambda also depends on model specification (Anselin, 2002; 2003; Gerkman, 2010).

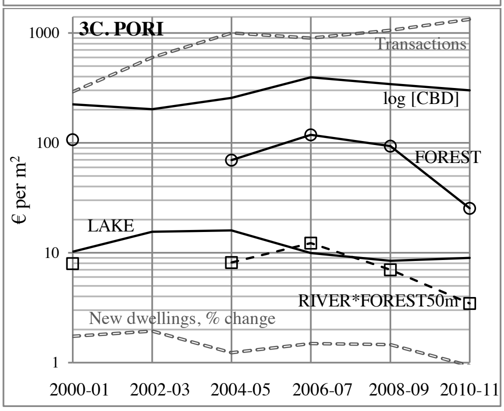
Lastly, a preliminary prompt was conducted into the temporal variation of the estimated marginal effects. While spatial analysis highlights an important dimension of the housing market, it should be kept in mind that price differentiation is naturally not limited to spatial processes like those in the focus of this study. The temporal variation of the discussed marginal effects confirms that the identified spatial dynamics should be placed alongside a broader set of economic and policy factors (Figures 3a, 3b and 3c).

In particular, even after using inflation-adjusted prices, the marginal values exhibit a significant drift from 2000 to 2011, with sharp changes in a few individual years. Generic reasons for this are insufficient residential construction as compared to demand, which is in turn driven by employment and population trends, as well as insufficient rental units. Yet, these generic factors have differentiated effects on the implicit prices of housing attributes, including ecosystems. These differentiated effects—that is, the assumed housing supply and employment trends influence different marginal values in different ways—might be due to variation in the scarcity of these characteristics, possible vintage (drift) effects in the preference scales of home seekers, and interactions between the aforementioned and other effects.

Similarly, further analysis is needed on the sensitivity of the marginal effects of most ecosystems to changes in the volume of real estate transactions, at the same year or with a time lag. Assuming that the volume of transactions is a reliable indicator of the wealth present in the housing market each year, it might be interesting to see whether the amount of money present in the system influences the value of urban ecosystems. However, it should be noted that the transaction volume is partly disturbed by real estate brokers entering or exiting the voluntary data collection scheme. Lastly, an interesting aspect of the temporal variation is that one can discern here, too, the different nature of the CBD and the coastline from the rest of the ecosystem types. A cluster analysis of curves should be able to yield clusters of hedonic attributes in terms of their temporal drift. Similarly, time series analysis should be able to illuminate much of the temporal behaviour in the estimated marginal effects.

FIGURE 3: TEMPORAL VARIATION OF THE ESTIMATED MARGINAL EFFECTS





Notes:
1. Marginal effects in € per m².
2. Espoo: The coefficient of FOREST for 2002-03 is statistically insignificant and is omitted.
3. Pori: Estimations for FOREST and RIVER*FOREST50m were not possible for the 2002-03 period.
4. Transactions (amount of) and new dwelling production are used as indicators of broader economic influences.

5 Conclusion: ecosystems in the urban system

The aim of this study has been to highlight the structural role of ecosystems in urban residential property value formation and differentiation, while controlling for other important factors. An amenity-based location model and hedonic function estimations across scales in Helsinki, Espoo and Pori have provided theoretical expectations and empirical support concerning the details of the studied structure. The majority of the estimations exhibit high statistical significance, model stability across samples of different years, and a satisfactory grasp of the total price variation. Even so, in a system as complex as the urban, the focus cannot be at the face value of the marginal effects. Variation in estimated hedonic coefficients is a reported source of uncertainty, largely stemming from the choice of empirical model and its parameters (Beron et al, 2010; Gerkman, 2012). This reinforces the necessity to emphasize structure rather than singular marginal values.

On one hand, the estimations show that ecosystems influence price across spatial scales. This behaviour is consistent with findings in urban complexity research on the fractal nature of several urban phenomena (Batty 2007). It is suggested to identify the marginal effects of the coarser scales with the exogenous environmental amenity effect outlined in Brueckner et al (1999), responsible for the formation of a city-wide morphology of property value. The exogenous effect diversifies with more kinds of ecosystems when moving towards the micro-scale, and is much more specific to the property or its immediate neighbourhood. It is suggested to view this as a separate mechanism that refines and fragments the value zones established by the general spatial equilibrium. Thus, it can be said that the city-wide mechanism and the few ecological factors that participate in it form value in an equilibrium fashion, whereas the micro-scale mechanism and its numerous factors differentiate value in a dynamic fashion. Furthermore, the same ecosystem can participate in both mechanisms. For instance, the presence of the sea as a large, ever-present geographical feature forms two general value zones (expected and observed high values nearby and lower values farther away), but inside the high value zone that has been formed in its general vicinity the sea further increases price for those few properties immediately next to it, along with plenty of other micro-factors. The above further strengthens the fractal behaviour assumption. Understanding price formation in this way is consistent with the characteristically noisy spatial morphology of value that is observed in the real world.

On the other hand, a number of details are visible. The diversity of marginal effects indicates that the housing market is sensitive to the specific kind of service that is received by the ecosystem, especially concerning urban green, as well as that it is often a combination of ecosystem services that influence value. Distance decay in the marginal values of the ecosystem is also evident. This suggests on one hand that the marginal effects can be quite local, and on the other that they are spatially variable. However, as previously noted, the concept of "local" must be understood properly since the models employed are global and most of the effects are smoothing out rather than disappearing. The endogenous amenity component suggested by Brueckner et al (1999) is present through the spatial error term of the estimated hedonic functions. The commonality between the two is thus far focused on the interpretation of both as a neighbourhood premium connected to culture, perception or similar spatial unobservable features; more statistical analysis is needed to verify the endogeneity character.

The indication that the urban ecosystem is active as a price determinant across spatial scales and highly contextual in its marginal effects brings forth three important implications for adaptation and sustainability in cities. Firstly, local agent action and citywide mechanisms have to be understood as one system, which replaces monolithic and top-down planning programs with a more pragmatic and sensitive to local conditions approach, as Batty (2007) has showcased. Secondly, as Brooks (2011) has discussed, either poles in the efficiency–equity continuum are unrealistic because they are both too general to grasp urban economic dynamics. In particular, it is erroneous to think of ecosystems either as something to be placed everywhere (equity) or something readily substituted (efficiency); ecosystems are structural elements of the urban economy and their true effects are much more complex than the equity–efficiency dipole is configured to grasp. Thirdly, the spatial and temporal particularities of the effects of the urban ecosystem and its services on urban economic behaviour have to become apparent, and here processes other than the spatial ones discussed in this text have to be taken into account; economic cycles, housing policy and housing supply deficiencies with respect to the demand placed by population and employment dynamics seem to influence also the value of ecosystems. All those elements are necessary whether the focus is on change of current, or adaptation to new ecological conditions, as the ecosystem is a major link between biophysical and socioeconomic phenomena in the city.

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Appendix: regression results at the disaggregate level

TABLE 3A: HEDONIC ESTIMATIONS AT THE DISAGGREGATE LEVEL, HELSINKI APARTMENTS, YEARS 2000–2011

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Intercept	7.156***	6.888***	7.575***	8.233***	9.26***	10.033***	12.189***	12.749***	12.294***	11.827***	14.034***	13.804***
DEBT	–.051	.568***	–.575***	–.583***	–.524***	–.734***	–.313***	–.509***	–.518***	–.66***	–.534***	–.616***
MAINT	–.039***	–.035***	.007	–.02**	–.04***	–.032***	– .054***	–.017	–.01	–.011	–.009	–.017·
ROOMS	–.067***	–.052***	–.129***	–.124***	–.1***	–.11***	–.119***	–.152***	–.142***	–.192***	–.254	–.236***
AGE	–.012***	–.01***	–.015***	–.018***	–.017***	–.017***	–.02***	–.021***	–.026***	–.023***	–.024***	–.021***
$[AGE]^2$	9.979e-5***	1.058e-4***	1.409e-4***	1.467e-4***	1.426e-4***	1.552e-4***	1.856e-4***	1.774e-4***	2.035e-4***	2.132e-4***	1.966e-4***	1.812e-4***
ONSALE	–.001***	–.001***	–.000	–.001***	–.000***	–.001***	–.002***	–.001***	–.001***	–.001***	–.000***	–.000*
FLOOR	.039***	.043***	.03***	.037***	.032***	.056***	.051***	.065***	.064***	.065***	.062***	.067***
BADCOND	–.269***	–.097***	–.332***	–.407***	–.392***	–.442***	–.453***	–.512***	–.601***	–.598***	– .543***	–.464***
AVGCOND	–.213***	–.11***	–.12***	–.181***	–.23***	–.28***	–.296***	–.259***	–.279***	–.237***	– .226	–.281***
OWNPLOT	.142***	.149***	.055·	.149***	.214***	.192***	.194***	.162***	.256***	.259***	.281	.304***
log [CBD]	–.372***	–.399***	–.416***	–.477***	–.535***	–.602***	–.73***	–.798***	–.803***	–.746***	– .932***	–.911***
log [SEA]	–.139***	–.124***	–.137***	–.117***	–.172***	–.197***	–.283***	–.266***	–.22***	–.209***	– .238***	–.236***
FOREST	–.002	–.002***	–.002***	–.001***	–.002***	–.002***	–.002***	–.002***	–.001**	–.002***	– .001***	–.001**
CBD*FOREST	1.391e-4	2.99e-7***	2.564e-7**	1.578e-7*	2.112e-7**	2.541e-7***	3.225e-7***	1.905e-7***	2.899e-7***	2.929e-7***	2.607e-7***	1.868e-7***
SPRECDENS	.021***	.023***	.03***	.027***	.016***	.021***	.01·	.02***	.022***	.018***	.024***	.021***
CBD*SPRECDENS	–3.298e-6***	–3.779e-6***	–4.545e-6***	–4.314e-6***	–2.853e-6***	–3.072e-6***	–1.969e-6*	–2.952e-6***	2.718e-6***	–2.473e-6***	–2.816e-6***	–2.19e-6***
LAMBDA (λ)	.625***	.578***	.446***	.598***	.704***	.728***	.793***	.64***	.655***	.559***	.597***	.608***
Negelkerke R^2	.67	.66	.65	.76	.79	.79	.84	.79	.76	.76	.79	.81
N (of properties)	1717	3296	2138	2617	3030	3483	4129	5201	4301	5231	5640	5200

Notes:
1. Significance levels: (***) 0.000; (**) 0.001; (*) 0.01; (·) 0.05.
2. Lambda is the spatially autocorrelated error component, interpreted as an unobserved neighbourhood effect on value.
3. The reported coefficients are interpreted as marginal effects and correspond to € thousand per m^2.
4. Log refers to the natural logarithm.

TABLE 3B: HEDONIC ESTIMATIONS AT THE DISAGGREGATE LEVEL, ESPOO APARTMENTS, YEARS 2000–2011

	2000-01	2002-03	2004	2005	2006	2007	2008	2009	2010	2011
Intercept	11.742***	10.005***	12.946***	12.625***	16.359***	16.148***	15.017***	13.576***	17.515***	18.109***
DEBT	–.51***	–.683***	–.807***	–.864***	–.963***	–.741***	–.575***	–.987***	–.846***	–.77***
FLOORSP	–.008***	–.009***	–.007***	–.009***	–.008***	–.009***	–.01***	–.012***	–.013***	–.01***
FLOOR	.022***	.018***	.028***	.006	.031***	.025***	.018·	.002	.031***	.038***
BADCND	–.121***	–.305***	–.217	–.213*	–.314***	–.47***	–.441***	–.398***	–.333***	–.252*
AVGCOND	–.118***	–.117***	–.171***	–.22***	–.233***	–.164***	–.181***	–.173***	–.173***	–.215***
AGE	–.012***	–.023***	–.059***	–.056***	–.047***	–.036***	–.039***	–.06***	–.06***	–.05***
$[AGE]^2$		1.774e-4·	7.027e-4***	5.992e-4***	4.647e-4***	2.016e-4·	2.752e-4*	6.3e-4***	5.404e-4***	3.164e-4**
log [CBD]	–.854***	–.635***	–.837***	–.721***	–1.185***	–1.134***	–1.02***	–.787***	–1.158***	–1.255***
log [SEA]	–.129***	–.143***	–.179***	–.236***	–.166***	–.19***	–.183***	–.209***	–.25***	–.227***
PARKDENS	.097**	.133***	.087·	.095·	.024	.087*	.099*	.107*	.168***	.3***
log [FORES]	–.003***	.002	–.025·	–.028**	–.027*	–.012	–.008	–.028**	–.001*	–.027
LAKEVIC	.179***	.124·	.209·	.135*	.469***	.247*	.307*	.338·	.3	.403**
ONSALE				–.000·	.000	–.001**	–.001***			
YEAR	–.094***	.129***								
LAMBDA (λ)	.667***	.672***	.686***	.837***	.786***	.578***	.466***	.588***	.554***	.667***
Negelkerke R^2	.71	.74	.74	.86	.87	.75	.67	.76	.76	.79
N (of properties)	1145	1274	667	941	1048	1214	968	1143	1227	1209

Notes:
1. Significance levels: (***) 0.000; (**) 0.001; (*) 0.01; (·) 0.05.
2. Lambda is the spatially autocorrelated error component, interpreted as an unobserved neighbourhood effect on value.
3. The reported coefficients are interpreted as marginal effects and correspond to € thousand per m^2.
4. Log refers to the natural logarithm.

TABLE 3C: HEDONIC ESTIMATIONS AT THE DISAGGREGATE LEVEL, PORI APARTMENTS, TWO-YEAR PERIODS DURING 2000–2011

	2000-01	2002-03	2004-05	2006-07	2008-09	2010-11
Intercept	3.395***	3.41***	4.332***	5.251***	5.06***	4.826***
DEBT	–.685***	–.951***	–.927***	–1.01***	–.812***	–.763***
FLOORSP	–.000**	–.003***	–.004***	–.004***	–.005***	–.004***
FLOOR	.018*	.008·	.015***	.016***	.01*	–.025***
AGE	–.017***	–.013***	–.023***	–.017***	–.028***	–.031***
$[AGE]^2$	1.109e-4***	6.277e-5***	1.448e-4***	8.845e-5***	2.055e-4***	2.113e-4***
BADCND		–.216**		–.372***	–.367***	–.359***
AVGCOND		–.151***	–.075***	–.133***	–.158***	–.154***
log [CBD]	–.225***	–.203***	–.257***	–.395***	–.342***	–.299***
LAKE	–.000**	–.000***	–.000***	–.000***	–.000***	–.000***
FOREST	–.001**		–.001***	–.001***	–.001***	
FORES50*RIVER	–.001·		–.000***	–.000***	–.000*	
ONSALE					–.000**	–.000***
NORTH		–.276***	–.392***	–.349***	–.321***	–.241***
YEAR	–.064.	.068***				.082***
LAMBDA (λ)	.329***	.636***	.73***	.647***	.663***	.474***
Negelkerke R^2	.59	.79	.88	.84	.81	.78
N (of properties)	292	599	1002	900	1059	1331

Notes:
1. Significance levels: (***) 0.000; (**) 0.001; (*) 0.01; (·) 0.05.
2. Lambda is the spatially autocorrelated error component, interpreted as an unobserved neighbourhood effect on value.
3. The reported coefficients are interpreted as marginal effects and correspond to € thousand per m^2.
4. Log refers to the natural logarithm.

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Planning for green infrastructure: The spatial effects of parks, forests, and fields on Helsinki's apartment prices

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ABSTRACT

As the importance of urban green spaces is increasingly recognised, so does the need for their systematic placement in a broader array of socioeconomic objectives. From an urban planning and economics perspective, this represents a spatial task: if more land is allocated to various types of green, how do the economic effects propagate throughout urban space? This paper focuses on the spatial marginal effects of forests, parks, and fields and estimates spatial hedonic models on a sample of apartment transactions in Helsinki, Finland. The results indicate that the capitalization of urban green in apartment prices depends on the type of green, but also interacts with distance to the city centre. Additionally, the effects contain variable pure and spatial spillover impacts, also conditional on type and location, the separation of which highlights aspects not commonly accounted for. The planning of green infrastructure will therefore benefit from parameterizing interventions according to location, green type, and character of spatial impacts.

1. Introduction: The Spatial Economic Context of Implementing Urban Green

Green infrastructure (GI), with its capacity to provide ecosystem services (ES) in a comprehensive manner across an urban area, has been proposed as a key element in sustainable urban planning, as well as in adaptation and resilience to the effects of climate change (Renaud et al., 2013; European Commission, 1994, 2011, 2013; IPCC, 2012; European Environment Agency, 2011). From a rational planning perspective, the implementation of GI in cities represents the task of modifying a tightly interdependent spatial system, where the typical underutilization of natural areas needs to be addressed in a way that urbanization's fundamental non-ecological benefits are also maintained. Additionally, since the urban economic system is as sensitive to land use choices as the provided mix of ES is, the further question arises of knowing the differences between the economic effects of alternative green solutions. Besides planned spatial interventions, the above questions are valid also in the context of unplanned changes in the natural stock of an area, e.g., due to species changes following gradual change in climate conditions or one-time extreme weather events.[1]

In practice, the systematic implementation of GI implies trade-offs with other urban functions, and poor evaluation of green interventions in relation to a broader array of socioeconomic objectives may bring adverse effects (Wolch et al., 2014; Perino et al., 2014). These relate to the fact that the configuration of urban land use follows a specific spatial optimization logic. In order to maintain a sufficient amount of agglomeration benefits, the allocation of space to highly productive and therefore competitive functions (e.g., housing, public services, and jobs) is favoured and, in turn, functions typically regarded as less competitive—including ecosystems—tend to be minimized, substituted, or expelled. So, in theory, the relative location and size of objects matter greatly for the socioeconomic prosperity of cities, since this spatial logic has historically delivered fundamental benefits, such as optimal provision of services and employment, tight social networks, and efficient distribution and exchange of goods. The need to reconsider this logic relates to its inherent externalities (e.g., pollution, flooding and inadequate handling of storm water, noise, health effects), the effects of which are exacerbated by the changing climate. Ultimately, the issue at stake is integration and evidence-based decision support. Even though the importance of GI is obvious, it is not as straightforward to understand what the increased allocation of space to previously expelled, space-competing functions entails for the urban economy.

The above questions involve phenomena at multiple spatial scales (James et al., 2009). This study focuses on finer scales and on plannable features inherent to apartment properties and their immediate surroundings. The study assumes that the spatial effects of urban green as measured in the housing market are useful in understanding trade-offs involved in the implementation of GI at fine spatial scales. The analysis estimates spatial hedonic models on a sample of apartment

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[1] An example is a recent drought in Helsinki that resulted in the loss of pines and their replacement either by species that are more heat-resistant, or by empty land and more droughts.

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transactions in Helsinki, Finland for the years 2000–2011. Firstly, the marginal effects of three types of green spaces (forest, park, and field) and their interaction with distance to the city centre are estimated and compared. Subsequently, the spatial spillover impacts (direct, indirect, and total) for the capitalization of forests, parks, and fields in apartment prices are calculated. These spillovers are qualitatively different from distance decay (from a green space) or geographically variable effects. They introduce an additional policy-relevant aspect, indicating the extent to which the benefits of a certain green type remain at (or originate from) the implementation location or diffuse to (and from) neighbouring ones. The focus on apartment prices is motivated in light of sustainable urban growth and mixed, denser solutions for housing, which almost invariably imply apartment solutions for the urban population. The following section discusses in brief the urban economic context of green amenities, overviews past hedonic valuation studies, and explains the focus on specific spatial effects.

2. Urban Green in Housing Price Formation and Differentiation

The provision of multiple (Davies et al., 2011; Givoni, 1998) and often non-substitutable (Hauru et al., 2012) ES by green spaces makes them influential amenities in the urban economic context. As such, their participation in the formation of residential property value can be approached by referring to a residential location model (Muth, 1969; Mills, 1967; Alonso, 1964), modified to reflect the structural role of natural amenities. Brueckner et al. (1999) show that, in addition to transportation cost and preferences on dwelling type and size, the spatial variation of amenities will co-determine the equilibrium outcome. Households seek to locate near exogenous natural and historical amenities, and the wealthy will typically outbid the rest for locating near these amenities. The outcome of this process is reflected in the observed morphology of housing prices; high values are typically associated with amenity-rich locations, such as the urban core, green spaces, and coastline.

Empirically, the participation of natural amenities in price formation and differentiation is detected in realized housing market transactions by estimating the sensitivity of property prices towards the quantity, type, and quality of amenities. For ecological amenities, De Groot et al. (2002) and Bateman et al. (2010) enumerate methodologies for linking ES to monetary value, with hedonic analysis being the most relevant approach in the housing market. Hedonic price theory suggests that housing is a composite commodity, representing for consumers more than just a shelter; proximity to amenities and services are examples of other attributes bundled together in housing. By estimating the market price of dwellings as a function of their attributes, it is possible to derive an implicit value for each attribute (Brueckner, 2011; Sheppard, 1999; Dubin, 1988; Quigley, 1982; Rosen, 1974). The estimated coefficients of the attributes are interpreted as their marginal values or effects. By analysing the variation of the type, quantity, and quality of hedonic attributes in relation to the corresponding variation in property prices, inferences can be made about the implicit value and relative importance that consumers tend to attach to ecological amenities, as well as the willingness to pay (WTP) for them (Freeman et al., 2014). The estimated effects are also useful in comparing different types of urban green with respect to relative importance and implicit value, as different types of green can be approached as distinct hedonic attributes.

In Finland, Tyrväinen (1997) reports that a 100 m increase in the distance of a dwelling to wooded recreation areas decreases its market price/m^2 by 42 FIM (€ 7.14) in the city of Joensuu, while Tyrväinen and Miettinen (2000) report that a 1 km increase in the distance of a dwelling to a forested park decreases its market price by 5.9% on average and a direct view to a forested area increases price by 4.9% in the city of Salo. In both studies as well as in international literature (e.g. Czembrowski and Kronenberg, 2016), the authors observe a notable dependence of the estimations on the type of green and the variable that represents it. The consensus in literature is that urban green is positively valued in the housing market; the meta-analysis studies of Brander and Koetse (2011), Perino et al. (2014), and Siriwardena et al. (2016) provide thorough summaries.

As the housing market has a strong geographical dimension, the hedonic approach is often augmented, among others, with the concepts of spatial non-stationarity and spatial spillovers. Spatial non-stationarity concerns the cases where regression coefficients vary across geographical space (Bivand et al., 2008; Lloyd, 2007; Schabenberger and Gotway, 2005; Fotheringham et al., 2002). For the present context, this suggests that the marginal effects of green will vary across different parts of the city and may be altogether zero in some locations, from a global point of view, regardless of the local distance decay function to individual green patches (e.g. Cho et al., 2011). For instance, empirical studies report a general decrease in the value of formal green patches as population density decreases (Brander and Koetse, 2011) or ownership of private green spaces increases (Tu et al., 2016). In addition, the first law of geography (Tobler, 1970; Miller, 2004) suggests that geographical locations are in fact interdependent so that a change in one location will affect neighbouring locations and vice versa. This implies that the marginal effects measured in hedonic regressions are the combination of pure effects due to the characteristics of a given property and spatial spillover effects due to interaction with neighbouring properties (LeSage and Pace, 2009; Anselin, 2003, 1995, 1988).

In summary, considering green spaces in connection to the spatial morphology of property prices, and drawing from the discussed literature, the estimations of this paper aim to explore the following three spatial effects of green interventions. Firstly, different types of green should be explored in more detail as amenities that are distinct from each other, which may entail different price effects, too. Secondly, different parts of the city, notably the core and periphery, are so fundamentally different, that a given solution will have geographically variable effects. Thirdly, as cities are systems of spatially interdependent locations, a green intervention at one location affects the rest of the system and vice versa. Green interventions will thus generate spatial spillover effects that propagate throughout the city in varying intensities and through varying channels. The first assumption is tested by estimating the marginal effects of distances to forests, parks, and fields; the second by including an interaction of the effects with distance to city centre; the third by separating pure from spatial spillover impacts.

3. Models and Assumptions

The particular view of green space assumed in the previous sections motivates the use of spatial regression models as better equipped to provide insights to the stated urban planning questions than non-spatial models. In addition, spatial regression models are capable of addressing estimation issues that are characteristic to spatial data analysis and hedonic datasets. Details about the foundations, methodology, and application of such models are found, among others, in Gerkman (2012), Anselin et al. (2010), LeSage and Pace (2009), Anselin (2003, 1988), and Dubin (1988).

Unobserved effects that exhibit spatial dependency are frequent in hedonic analysis due to hard-to-operationalize or non-decomposable spatial concepts like neighbourhood prestige or (un)attractive design. In that case, the residuals of ordinary least squares (OLS) estimations will be spatially autocorrelated and violate the i.i.d. error assumption. The first-order autoregressive spatial error model (SEM) addresses this problem by separating the residuals into a spatially autocorrelated component and an uncorrelated random error (model 1):

$$\mathbf{y} = \mathbf{X}\beta + \lambda\mathbf{W}\mathbf{u} + \epsilon, \tag{1}$$

where $\mathbf{X}$ is a matrix of hedonic attributes, $\mathbf{W}$ a spatial weights matrix, $\mathbf{Wu}$ a spatially autocorrelated error term, ϵ a random error term, and β, λ coefficients. The interpretation of coefficients in the SEM is the same as in OLS, while the spatial error term is usually seen as an uninterpretable instrument that clears residuals from spatial autocorrelation.

The assumption of spatial non-stationarity in the effects of green across the city can be explored by checking whether the magnitude of the price effect of distance to green is conditional on distance to the city centre. It is assumed that inserting a linear interaction term for each ecological variable in model 1 will serve this purpose. If $\mathbf{c}$ denotes distance to the city centre (CBD) and $\mathbf{g}_j$ distance to green with $j = \{$forest; park; field$\}$, '$\mathbf{g}_j{*}\mathbf{c}$' denotes the interaction of the two variables, and ζ, η, κ are regression coefficients for the two new variables and their interaction term, model 1 can be re-formulated as:

$$\mathbf{y} = \mathbf{X}\beta + \left\{\zeta\mathbf{c} + \eta\mathbf{g}_j + \kappa\left(\mathbf{g}_j * \mathbf{c}\right)\right\} + \lambda\mathbf{W}\mathbf{u} + \epsilon, \tag{2}$$

In the occasions that the spatial common factor hypothesis is satisfied, SEMs are nested into a larger model, which includes spatially lagged forms of the dependent and independent variables. The resulting specification is called the spatial Durbin model (SDM) and is used to separate and simulate spatial impacts important for urban planning and decision-making:

$$\begin{aligned}\mathbf{y} = \rho\mathbf{W}\mathbf{y} + \mathbf{X}\beta + \vartheta\mathbf{W}\mathbf{X} + \left\{\zeta\mathbf{c} + \eta\mathbf{g}_j + \kappa\left(\mathbf{g}_j * \mathbf{c}\right)\right\} \\ + \left\{\varphi\mathbf{W}\mathbf{c} + \xi\mathbf{W}\mathbf{g}_j + \omega\mathbf{W}\left(\mathbf{g}_j * \mathbf{c}\right)\right\} + \epsilon,\end{aligned} \tag{3}$$

where the endogenous term $\mathbf{Wy}$ is the spatially lagged form of the dependent variable, $\mathbf{WX}$, $\mathbf{Wc}$, $\mathbf{Wg}_j$, $\mathbf{W}(\mathbf{g}_j{*}\mathbf{c})$ are the spatially lagged forms of the independent variables, and ϑ, φ, ξ, ω are coefficients for the newly introduced terms.

The difference of SDM model 3 from SEM model 2 is the replacement of the spatially autocorrelated residual with the endogenous lagged form of the dependent variable and exogenous lagged forms of all the independent variables. In a sense, the SDM attempts to identify the unobserved spatial interaction captured in SEM's spatial error term by estimating spatially weighted effects of the dependent and each of the independent variables.

However, the estimated marginal effects of the hedonic attributes of model 3 are not interpretable at their face value, because the specification includes the dependent variable in both sides of the equation. Solving for the dependent variable shows that the effect of each variable on y consists of 'pure' and 'spatial spillover' effects, that is, of the impact of a region's own attributes plus the cumulative impacts spilling over from the attributes of neighbouring regions. LeSage (2008) and LeSage and Pace (2009) propose to render the coefficients interpretable by separating them into direct, indirect, and total impacts, depending on the geographical origin of the effect. Thus, if the interest is the marginal effect dy/dx in a typical region of an inter-dependent spatial system, then: direct is the effect due to changing x only at that particular region; indirect is the effect due to changing x in the neighbouring regions; and total is the effect due to a simultaneous system-wide change in x (LeSage, 2008). A region in the present case is interpreted as an individual property and its immediate vicinity.

The use of spatial matrix W for identifying and estimating spatial effects means that explicit assumptions about space and spatial interaction need to be made. In this study, the notion of 'space' is operationalized as the 1st order von Neumann neighbourhood of each property in the sample. Pre- and post-estimation specification tests confirmed the applicability of SEM model 2 to the sample, while the spatial common factor hypothesis verified that model 2 can be expressed as SDM model 3.

4. Data

The analysis has used approximately 44,300 apartment transaction records from the municipality of Helsinki ($\approx$ 536,000 inhabitants, 21,655 ha). The data record the selling price and other monetary characteristics of the property together with its postal address and several structural characteristics.[2] The monetary variables (price, debt, maintenance cost) were de-trended by adjusting for inflation with 2011 as the reference year and normalized to represent m^2 figures. The geographical coordinates of the observations were retrieved from the street address by a geo-reference operation, and land use and technical infrastructure maps were used to calculate additional hedonic variables that measure the distance of each property to ecological attributes and main transport lines. The procedure produced what Dubin (1988) describes as the structural, locational and neighbourhood characteristics of the dwelling, suitable for the estimation of spatial hedonic functions. Table 1 describes the analysed variables; the environmental variables are discussed in more detail in the following paragraphs.

The ecological variables were constructed by associating the geocoded transaction points to information extracted by land use maps. More specifically, the 10 m SLICES land use/cover product by the National Land Survey of Finland was used to extract three main classes: forest, park, and field. The names are translations from Finnish, while the land uses they represent are predefined by the data provider. Forests refer to predominantly tree-covered patches and aggregate various classes of tree species. Parks refer to patches with a varying mixture of natural and man-made features that include, for instance, trees, bushes, lawn, ground, and paved or unpaved pathways. Fields refer to predominantly agricultural fields and is an aggregate class including any type of crop and activity status (actively cultivated or inactive). Other natural land uses such as bare rock and soil, sand, gravel, peats, and wetlands are not included in the three classes. Fig. 1 provides indicative examples of the three land uses.

Following the extraction of forest, park, and field patches, maps of the Euclidean distance of every location of the metropolitan region to the perimeter of these patches were created. The procedure was repeated for the land use maps of years 2000, 2005, and 2010 and each observation point was overlaid on the distance map nearest to transaction year, in order to capture changes in the land use composition of the urban region. Distance to the coastline was calculated in a similar way. The spatial resolution of the land use maps implies that a patch of land has to be larger than 10 by 10 m^2 to be detected and classified. The implication for the analysed dataset and the interpretation of the estimations is that distances to green areas should be understood as distances to sufficiently large and therefore identifiable by land cover/use maps patches of green. Thin rows of trees are absorbed to the surrounding land cover type, if they are < 10 m wide, so that the distance of properties to road-side trees and then to a park is essentially distance to a park only.

A lot size variable is included to ensure that the ecological coefficients do not reflect the effect of large lots belonging to the property. Such a risk is introduced due to the high spatial resolution of the land use data, where the measured distances to green spaces may also include patches that belong to the parcels of the dwellings. In addition to including a lot size variable, the land use data used in this study pose a reduced risk of suffering from the above issue. These data do not classify lots or parcels belonging to residential properties as natural green spaces. Such patches are classified as man-made residential land use. Although data capture, classification, and spatial averaging errors in the source maps cannot be ruled out, this risk is further minimized by the fact that the analysed dwellings are apartments in an intensely quality-checked area (the capital city), and thus their lots are classified with high certainty as residential. It is thus reasonable to assume that the captured marginal effects relate only to distinct and formally designated green spaces.

Similarly, three variables measuring distance to major transport infrastructure are included to ensure that the estimations do not suffer

[2] These data are voluntarily collected by a consortium of Finnish real estate brokers and the dataset is refined and maintained by the VTT Technical Research Centre of Finland Ltd. As not all real estate agencies participate, this dataset represents a sample (albeit rather large) of the total volume of transactions.

Table 1
The variables of the analysis with mean values.

Variable	Description	Unit	Mean
PRICE	Selling price per m^2, 2011 prices	€ thousand per m^2	3.302
DEBT	Debt component[(a)], 2011 prices	€ thousand per m^2	0.187
MAINT	Monthly maintenance cost, 2011 prices	€ per m^2	3.245
FLOORSP	Floor-space	m^2	56.2
ROOMS	Rooms, excluding kitchen	Multinomial (1–9 rooms)	2.169
FLOOR	The floor on which the apartment is situated	Multinomial (1st – 9th floor)	2.99
AGE	Difference between selling and construction year	Years	48.24
BADCND	Bad condition	Dummy (1: bad, 0: otherwise)	0.06
AVGCND	Average condition	Dummy (1: average, 0: otherwise)	0.328
LOTSIZE	Lot size	m^2	1842
CBD	Distance to the central business district[(b)]	Kilometres	5.376
RLINE	Distance to railway track	Kilometres	1.259
MLINE	Distance to above-ground metro line	Kilometres	2.515
MJROAD	Distance to major roads	Kilometres	0.537
SEA	Distance to the coastline	Kilometres	1.26
FOREST	Distance to the nearest forested area	Kilometres	0.088
PARK	Distance to the nearest park	Kilometres	0.294
FIELD	Distance to the nearest field	Kilometres	1.294

[(a)] Properties in apartment blocks or row houses are usually managed by a housing cooperative/committee. Large maintenance tasks (e.g., roof, piping, or structural renovations) are undertaken by the housing committee and financed by a dedicated loan. The property's debt component is the portion of that loan that corresponds usually to the size of the property; it bounds the property rather than the owner, and passes from one owner to the next when the property is sold.
[(b)] CBD has been defined as the point in Helsinki's centre with the highest density of commercial establishments.

from the omission of noise or air pollution effects. The included variables measure distances to rail lines (which service commuter and long distance trains), above-ground metro lines (which service the segment of Helsinki's metro exposed to the surface and surrounding properties), and main road transport lines (which include type I and II highways and multilane roads). Remaining problems of spatially correlated omitted variables are addressed by the spatial models described in Section 3, which by definition clear estimates from this type of bias.

While the robustness of the housing transaction data has greatly benefited this study, similar availability cannot be presupposed in the developing world, where urban ES is a key issue. Assuming that transaction microdata is inaccessible or unsystematically collected, a way out is the use of aggregate, social media, or soft-GIS information. The models of this study are applicable to aggregate data, as long as the interpretation and policy recommendations avoid the ecological fallacy and focus on neighbourhoods rather than individual properties. Alternatively, the analysis of social media data is increasingly used in conservation and ES research (Wood et al., 2013; Di Minin et al., 2015). Typical steps would be to access the public API's of social media platforms, extract or deduce relevant information, and proceed with spatial hedonic analysis. Lastly, soft-GIS uses crowd-sourced observations to collect valuation-relevant information that is unavailable via more conventional routes (Brown et al., 2014; Brown and Kyttä, 2014). A typical setup would be the creation of a web or mobile platform that asks residents to tag properties or locations with encoded or free-form information on the characteristics of locations and properties and/or their price level. The effectiveness of this approach largely depends on the available technical infrastructure, data sharing culture, and method used to convert qualitative to quantitative data; its success and accuracy, however, has been demonstrated (Haklay and Weber, 2008; Haklay, 2010). In the last two cases variables used in this study but unavailable elsewhere can be produced by processing the mined information with publicly available or custom-made inference algorithms. Well-trained inference algorithms—using, for instance fuzzy logic, neural networks, or hybrid approaches—have the capacity to infer price levels and other difficult-to-collect quantities from sparse or qualitative information.

5. Marginal Effects and Urban-core-to-fringe Gradients

SEM model 2 was estimated firstly on the full sample (2000 — 2001) and subsequently on six biannual subsets (2000–01; 02–03; 04–05; 06–07; 08–09; 2010–11). The estimations were implemented in the 'R' software (R Core Team, 2016) in the spatial econometrics module 'spdep' (Bivand et al., 2016). The 'GeoDa' software (Anselin et al., 2005) was used to generate the spatial weights files.

The full-sample estimation (Table 2) explained 78% of price variation and returned the expected signs for all hedonic coefficients, except for that of distance to a forest. An increase in the debt and maintenance costs and a decrease in the condition of the property decreases price/m^2. Additional rooms have a negative effect, reflecting the diminishing marginal utility of additional units of space. Increase in the property's age decreases price until historical status becomes relevant and price increases again. The yearly dummy variables (omitted from Table 2) are

Fig. 1. Examples of green areas classified as forest (left), field (middle), and park (right).

Table 2
Spatial error estimation results, full sample.

Coef. (std. error)							
INTERCEPT	4.301***	[AGE]^2	0.000***	LOTSIZE	0.000	FOREST	0.331***
	(0.036)		*(0.000)*		*(0.000)*		*(0.090)*
DEBT/m^2	−0.615***	FLOOR	0.067***	RLINE	0.050***	FOREST ∗ CBD	0.004
	(0.008)		*(0.002)*		*(0.005)*		*(0.024)*
COST/m^2	−0.012**	BADCOND	−0.370***	MLINE	0.064***	PARK	.−0.509***
	(0.002)		*(0.011)*		*(0.004)*		*(0.065)*
ROOMS	−0.163***	AVGCOND	−0.234***	MJROAD	0.120***	PARK ∗ CBD	0.061***
	(0.003)		*(0.005)*		*(0.016)*		*(0.007)*
AGE	−0.029***	CBD	−0.173***	COAST	−0.096***	FIELD	0.0148***
	(0.001)		*(0.005)*		*(0.010)*		*(0.011)*
						FIELD ∗ CBD	−0.035***
							(0.003)
N	45,982	Pseudo R^2	0.78				

Notes:
1. Significance ranges: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1.
2. The unit of the ecological independent variables is distance to the green feature in kilometres.
3. The unit of the dependent variable is the property's selling price in € thousand per square metre.

significant, indicating a drop in the average level of selling price/m^2 from 2000 to 2001, followed by an increase from 2002 onwards. Increased distance to the city centre and coastline decrease price, whereas lot size is not significantly different from zero. The coefficients of the proxies for noise and air pollution disamenities are significant; a 100-meter increase in distance to rails increases average m^2 price by 0.15%, while the corresponding increase for over-ground metro line is 0.19% and for major road is 0.36%.

The estimation supported the assumption of a CBD gradient in the marginal effects of parks and fields. Increased distance to a park decreases prices in the city centre, or, conversely decreasing the distance of a downtown property to a park increases its price, with the effect gradually declining as distance to the CBD increases. The maximum effect is estimated to a decrease of 1.5% in the m^2 price when distance to a park increases 100 m, which is in the same range to the effect of recreational forests in the study of Tyrväinen (1997) that reports a corresponding increase of 0.5% (after currency conversion and average price normalization). However, the respective amenities are not directly comparable beyond a loose association of recreation to both types. Increased distance to fields decreases price in the urban fringe, or conversely, decreasing the distance of a suburban property to fields increases its price. The maximum effect along this gradient is a decrease of 1.1% in m^2 price when distance to a field increases by 100 m.

The regression is problematic in understanding the effect of forests. It indicates that increased distance to a forest increases price throughout the city with no statistically significant CBD gradient. Interestingly, a similar result is reported by Tyrväinen (1997) for the effect of distance to forest parks, who attributed it to non-fulfilment of the conditions for capitalization (Starret, 1981) and to dweller preferences on the specific tree type in forest parks. Additionally, Tyrväinen (1997) and Tyrväinen and Miettinen (2000) note that samples that are aggregated from years with varying macroeconomic conditions may pose estimation problems. Table 3 indicates that the present sample does have such variations as indicated by the somewhat sharp fluctuations in regional unemployment rates.

This ambiguity with the effect of forests was resolved by repeating the estimations firstly on biannual samples and secondly on the full sample with a model that separates pure from spatial spillover effects. Both alternatives maintained similar coefficient values for parks, fields, and the remaining hedonic variables. The rest of this section discusses in more detail the effects of parks, forests, and fields as estimated on the biannual samples, while Section 6 discusses the separation of pure and spatial spillover effects in the full sample.

Fig. 2 summarizes the effects per green type as estimated in the biannual subsets, showing the variation between subsets and multiyear average. The full results are provided in Table A-1 of the Appendix A. The graphs display only the years in which both the maximum (minimum in the case of fields) marginal effect (FOREST, PARK, FIELD) and its interaction term (FOREST ∗ CBD, PARK ∗ CBD, FIELD ∗ CBD) were statistically significant at the 95% margin, so that the gradient effect $\eta \mathbf{g}_j + \kappa(\mathbf{g}_j * \mathbf{c})$ of model 2 can be discussed with certainty. The graphs indicate a clear urban-core-to-fringe gradient for the three green types, as well as different magnitudes and gradient slopes between types.

The maximum effect of distance to a forest or park is at the urban core, while that of distance to a field is in the urban fringe. On a multiyear average, the effect of a 100 m increase of distance to a forest is a decrease of 3.7% in price/m^2 at 0 km from the CBD, which gradually drops to zero at 6 km from the CBD. The maximum effect is close to that reported by Tyrväinen and Miettinen (2000), which corresponds to a 5.3% decrease in price/m^2 for a 100 m increase in distance to a forested area for the average floorspace of 90 m^2 of their sample. The difference in estimates may be attributed to the fact that the valuation of Tyrväinen and Miettinen (2000) was conducted on a sample of terraced apartments as opposed to block apartments in this study. Terraced houses in Finnish housing markets have higher m^2 price than block apartments and are typically associated with wealthier households; it is assumed that the difference between the two studies relates to the higher WTP of wealthier households for green amenities. The maximum effect of distance to a park is estimated to 1.8% at the CBD, gradually dropping to zero at approximately 8 km from the CBD. As in the full-sample regression, the slope of the gradient of distance to a field is reversed; the maximum effect is 0.8% in the urban fringe (indicatively at 15 km from the CBD) and gradually drops to zero at approximately 8 km from the CBD. The difference between these estimates and the estimates of the full-sample regression is small (0.3% for parks and fields), except of the notable difference in the forest effects.

Table 3
Regional unemployment rates in Helsinki's NUTS-3 administrative region during 2000–11.

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
u %	6.3	5.5	5.8	6.5	6.5	6.1	5.4	5.0	4.8	6.2	6.4	5.8

The estimated gradients show that at approximately 6 to 8 km from the CBD, the marginal value of forests and parks diminishes to zero, while that of fields rises from zero. The estimations return negative effects in areas further than 6–8 km from the CBD for forests and parks, and in areas closer than 8 km to the CBD for fields. This is due to the assumed unbounded linear form of the gradient; it is therefore interpreted not as an actual discount, but as zero benefit. The maps in Fig. 3 (reproduced in color in the article's electronic version and in greyscale in its paper version) display the multiyear mean gradients (black lines in Fig. 2) as surfaces over Helsinki's urban morphology and also indicate the spatial distribution of Helsinki's GI and densities of residential building stock.

The urban-core-to-fringe gradients in the coefficients of green spaces merit further attention. The empirical literature points to scarcity arguments to explain this feature and highlights the influence of suburban residential development dynamics.

The decline of the implicit price of urban green as population density decreases is reported in both the North American and European contexts (Brander and Koetse, 2011; Perino et al., 2014; Siriwardena et al., 2016). The gradient has been related to scarcity-demand (Siriwardena et al., 2016) or scarcity-crowdedness arguments (Brander and Koetse, 2011). As population density increases, so does built-up density, which—as implied by the land use component in the spatial equilibrium of the Alonso-Muth-Mills model—results in scarcer natural spaces, raising the value of remaining green patches. Population density is proxied here by distance to the CBD; the municipality of Helsinki (as opposed to the broader metropolitan region) is monocentric with a decline of population and built-up density as distance to the CBD increases (Fig. 3 bottom right). Furthermore, it is reasonable to assume that the (as yet) non-substitutable capacity of green spaces to correct the environmental externalities occurring in the central areas of urban agglomerations adds to a pure scarcity argument. The estimations indicate that the minimization of the marginal value of forests and parks starts at approximately 6 to 8 km from the CBD. In this zone, the older and denser parts of Helsinki transition to a sparser morphology with more abundant nature and less intense environmental externalities. The estimated decrease of value with increased distance to the CBD also relates to the contingent valuation study of Tu et al. (2016), which found that ownership of a private garden decreases the WTP for living closer to an urban park, which in this study relates to an increased likelihood of private garden or yard ownership, typically associated with mid-to-low density residential land uses.

The CBD gradient in the marginal price of fields follows the reverse trend and begins to rise at approximately the zone in which the marginal price of forests and parks is minimized. Although the location at which this gradient becomes nonzero positive may be explained by the fact that fields in Helsinki are only found starting from approximately this zone (Fig. 3 bottom left), it cannot explain the rising prices when moving deeper into the suburban zone. Historical data and exploratory land use – transport modelling (available by request) indicate that development is particularly active in this area and advances via the consolidation of existing built-up clusters and their expansion into forests and fields. The built-up expansion is constrained in the north by an administrative border that encircles the municipality and in the south by the already intensely developed central parts of the city.

Roe et al. (2004) show that agricultural land near new suburban housing developments is the most attractive price compensation feature for relocating households. This can explain the positive values estimated for fields in this study, as the main component of the variable is agricultural land. The maximum magnitude of the effect is comparable to that of urban parks, which, too, is in line with hedonic literature reporting that agricultural fields have the capacity to increase the prices of nearby properties as much as other types of green spaces (Ready and Abdalla, 2005).

The perceived value is, however, conditional on the development prospects of the agricultural patches (Roe et al., 2004) and home buyers place higher value on open space when it is perceived as conservable (Geoghegan, 2002; Irwin, 2002), also in Finland (Tyrväinen and Väänänen, 1998). Concerning agricultural fields in the urban fringe, a scarcity argument has been proposed elsewhere: the highest WTP for agricultural land is expected when most of it has been developed (Roe et al., 2004). Given these suggestions, the estimated gradient for fields may also be taken as an indicator of the perception of suburban apartment buyers about the surrounding fields, namely that they are perceived as already scarce (fairly accurately, as seen in Fig. 3) but likely preserved. Furthermore, these scarce patches are near the administrative limit of the municipality and most of them have a pronounced conservation flavour—being, among others, municipal farms or adjacent to the protected ecosystems of the nearby rivers—which may strengthen the perception of these fields as conservable. One can thus argue that these conservation perceptions function concurrently with the high value potential of agricultural fields discussed by Roe et al. (2004), and since the conservation areas are mostly located at the outer administrative limit of the municipality, they cause marginal prices to

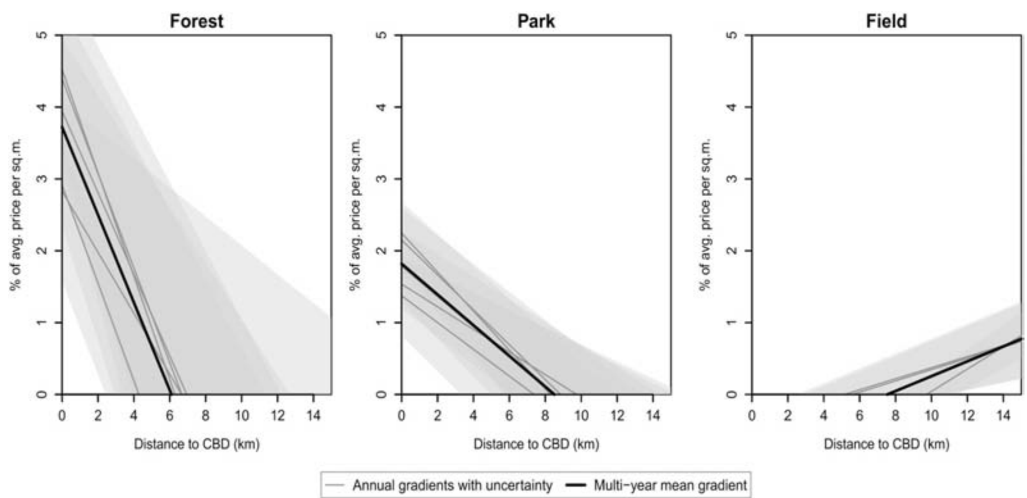

Fig. 2. Marginal effects and spatial gradients for forest (left), park (middle), and field (right). Grey lines and shaded areas denote the gradients and estimation uncertainty of statistically significant years. Black lines denote multi-year mean gradients.

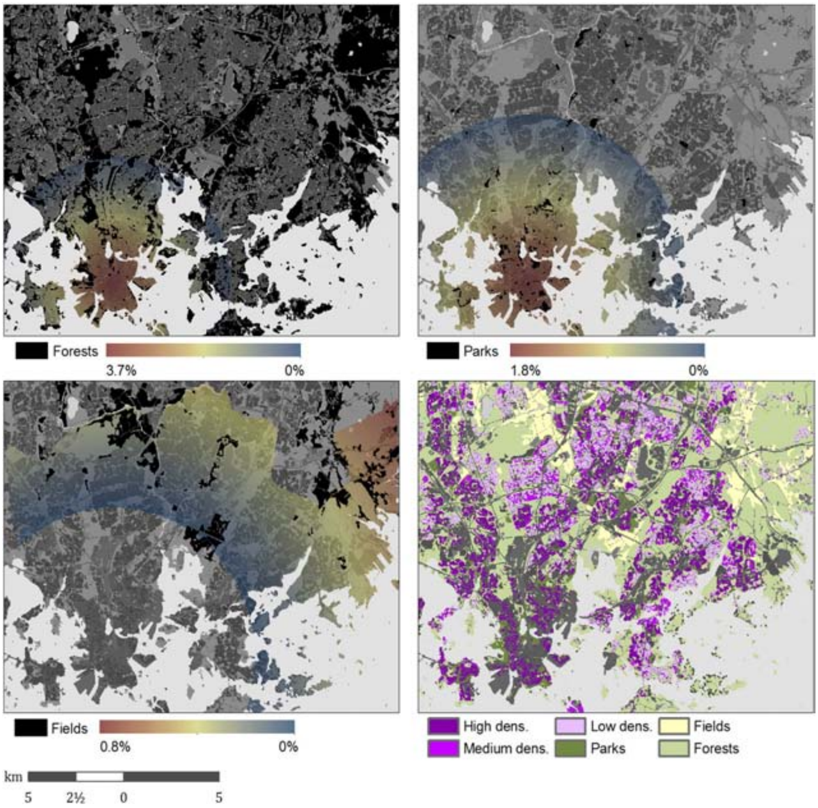

Fig. 3. Effect gradients of forested areas (top left), parks (top right), and fields (bottom left); each map also displays (in black) the spatial distribution of the respective green type. Helsinki's green infrastructure and residential densities are shown in the bottom right image.

gradually rise as properties approach this limit (i.e., with increased distance to the CBD).

Lastly, Ready and Abdalla (2005) report that when the alternative use of agricultural fields is low density residential, the patch does not affect the prices of nearby properties, whereas if the alternative is high density residential or commercial/industrial, it reduces prices of nearby dwellings. This is in line with the estimated gradient for fields. On one hand, moving closer to the CBD represents a higher likelihood of available land being converted to high density usage, represented here as a gradual drop to zero effect. On the other hand, the marginal price is estimated on apartment transactions, which are not the standard type of suburban development in Helsinki. As distance to the CBD increases, so does the likelihood of new development being low or medium density, which according to Ready and Abdalla (2005) means a higher expected value for agricultural fields.

The above discussion of the biannual estimates uses multiyear averages. The biannual variation in the magnitude and slope of the estimated effects is limited; in the maximum effect of distance to a forest it amounts to $\pm 1\%$, to a park $\pm 0.5\%$, and to a field it is negligible. Yet the temporal subsets eliminated the forest coefficient issue of the pooled sample while returning similar values for the rest of the effects. This feature is present also in regressions on single year samples, but could be attributed to small sample sizes. To check this, biannual samples (reported here) with large sample sizes (between approximately 5000 in 2000–01 and 10,000 in 2010–11) were constructed in order to rule out sample instability, but the temporal variation was retained. One could hypothesize that consumer confidence and purchasing power influences how much house buyers are willing to pay for green amenities. A competing hypothesis could be that perceptions about the present or future scarcity of the local natural environment might have influenced the measured marginal prices of distance to green. These hypotheses could not be explored here via, for instance, a second-stage hedonic analysis (Quigley, 1982; Brueckner, 2011).

While the temporal variation of the coefficients could be ruled out as instability, the negative amenity effect of forests in the pooled regression versus the positive effect in the biannual regressions is still an issue. This raises the question of why the same robust spatial specification produces contradictory conclusions about the effect of forests on temporally different samples. The following section presents a competing explanation for this ambiguity that focuses instead on the separation of pure from spillover effects.

6. Separating Pure and Spatial Spillover Impacts

While the hedonic valuation literature has been increasingly addressing the issue of spatially autocorrelated omitted variables via spatial specifications or other types of spatial controls (Kuminoff et al., 2010), contamination of the estimated effects by multiple waves of spatial spillover effects from neighbouring properties has not received much attention. As discussed in Section 3, in a spatially dependent market, the implicit price of an environmental amenity reflects not only the market transaction of a particular property (the typical hedonic valuation context); it may also contain the spillover of the same effect that diffuses from neighbouring properties.

In order to separate pure for spatial spillover effects, SDM model 3 was estimated as an alternative to SEM model 2 for the full 2000–2011 sample. Adapting LeSage (2008), and maintaining the interpretation of % changes in the m^2 price of a typical apartment, caused by a change in the distance to urban green, the spatial impacts are interpreted as follows. Direct are the price impacts of a change at the property itself, whereas indirect are the impacts that spillover from a change in neighbouring properties. If the change happens simultaneously in a city-wide fashion, this is reflected in the total impacts. The issue can be therefore approached by asking where a change happens and where the benefits go: at the property, neighbouring properties, or simultaneously everywhere.

Table 4 and Fig. 4 summarize the estimated spatial impacts. The estimation explained 79% of total price variation. The maximum direct impact of a 100 m increase of distance to a forest is a decrease in m^2 price by 1% at the urban fringe, gradually dropping to zero at approximately 9 km from the CBD; the maximum indirect impact is reverse with approximately 3.4% at the CBD, gradually dropping to zero at 4 km from the CBD; and the maximum total impact is 2% at the CBD, gradually dropping to zero at 3 km from the CBD. Concerning the effects of a 100 m increase of distance to a park, the maximum direct impact is 0.1% at the CBD, gradually dropping to zero at 3 km from the CBD; the maximum indirect impact is 2% at the CBD, dropping to zero at 10 km from the CBD; and the maximum total impact is 2.2% at the CBD, dropping to zero at 9 km from the CBD. The maximum direct impact of a 100 m increase in distance to a field is 2.5% at the urban fringe, gradually dropping to zero at 3 km from the CBD; the maximum total impact is 0.7% at the CBD, declining to zero at 8 km from the CBD; indirect impacts are negative and assumed as zero-benefit.

While the indirect and total impacts of forests are maximum at the CBD and declining farther away, their direct impact exhibits a gradient similar to that of fields and its sign at the CBD resembles that in the full-sample SEM model, which was taken as problematic. Given this evidence, however, it is reasonable to presuppose that the full-sample SEM model returned unexpected estimates for forests because it was unable to separate pure from spillover effects and the fact that indirect and direct impacts have opposite gradients.

The above figures indicate a few important differences in the spatial character of the marginal price effects of distance to forests, parks, and fields. Given the separation of pure and spillover effects, it is reasonable to suggest that decreased distances to all three green types capitalize positively in Helsinki's apartment prices, but only at the correct locations within the urban area and with a specific spatial impact character in mind. In particular, fields capitalize exclusively in the urban fringe and the effects concern exclusively changes at a certain property; spatial spillover of the price effects to/from neighbouring properties is zero and it takes a city-wide change (total impacts) to observe more widespread price changes. In contrast, parks capitalize exclusively at the city centre; the price effects are small at the concerned property and mostly spill over to (and from) neighbours. The capitalization of forests is double-natured as also found in Tyrväinen (1997); they capitalize at the concerned property only in the urban fringe, while the price effects in the urban core are spillovers to and from the neighbourhood.

Lastly, from a spatial policy viewpoint, the overlapping of the effect gradients is of interest. The gradients suggest that, all other things equal, certain zones are more flexible in the sense that more than one alternative green type can have positive price effects; in the zone of 0–4 km from the CBD the indirect effects of forests and parks overlap, while between 8 and 10 km the direct effects of forests and fields overlap. Nevertheless, as discussed previously, the spatial diffusion character of capitalization also varies spatially. The overlapping of impacts should not be therefore understood as an indication of substitutability, but rather as a way to correct the inability of one type of green to produce certain effects by complementing it with the ability of another type. This is evident, for instance, in 0–2 km from the CBD, where urban parks provide only direct benefits, but forests provide only indirect benefits; the use of both would provide both types of capitalization benefits, which is an interesting dimension in spatial economic planning.

7. Conclusions

This study has employed spatial hedonic specifications to assess two spatial aspects in the marginal effects of distance to forests, parks, and fields on apartment prices: the interaction of the estimated effect with a distance to the city centre gradient; and the spatial diffusion character of those effects along the same gradient.

The estimations indicate that the three different green types yield different marginal effects and these depend on location within the city and the nature of spatial spillovers generated. While it is fair to say that decreasing distance to all three green types has the potential to increase price/m^2, the realisation of this potential into actual benefits depends on refining the type of spatial impact and the location along the distance to the CBD gradient. Additionally, there are a few distinct zones along this gradient where the marginal effects of different green types overlap. These may be taken as a cautious indication of substitutability—with the discussed valuation literature in Section 5 supporting such interpretation—but it can more conservatively be taken to represent complementarity, as one type of urban green can cover for particular impacts that another type cannot provide at a certain location along the CBD gradient.

Obviously, the interpretation of pure versus spillover effects is central in this argument and the topic is not sufficiently developed in the hedonic context. In this study, it is proposed that the separation of pure from spillover impacts makes sense if one considers who pays versus who receives the benefits of a change in the distance to a certain green type; as seen above, the extent to which benefits diffuse in a spatially dependent market varies per green type and per location along the CBD gradient. Alternatively, one may elect to focus on where the change happens, rather than who invests. In this case indirect impacts become particularly important, because changes in the distance to green of neighbouring properties may affect the price of a given property without the property itself having experienced (or invested in) such a change.

Table 5 presents in a schematic manner this parameterization of benefits per location, type of green, and type of spatial intervention. The primary utility of this table is to illustrate that climate adaptation or other urban strategies that rely significantly on urban green ought to move towards a more detailed conceptualization of urban green and the price effects it may represent.

Although the results as such represent the marginal contribution of distance from green patches to housing prices, it should be noted that in planning practice such analysis refers to plannable green solutions

Table 4
Spatial impacts simulation results, full sample.

Coef. & signif.	FOREST	FOREST ∗ CBD	PARK	PARK ∗ CBD	FIELD	FIELD ∗ CBD
Direct	0.464***	−0.053·	−0.046***	0.015***	0.164***	−0.062***
Indirect	−1.110***	0.261***	−0.680***	0.066***	0.064***	0.032***
Total	−0.646**	0.208***	−0.725***	0.081***	0.228***	−0.030***

Notes:
1. Significance ranges: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1.
2. Simulated significances are based on $R = 1000$ replications.

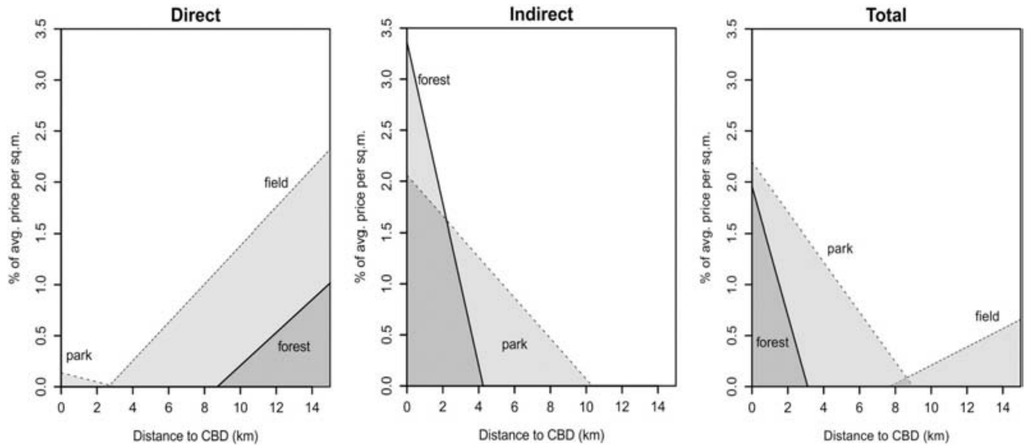

Fig. 4. Direct (left), indirect (middle), and total (right) spatial impacts of forests, parks, and fields.

or investment options. The results can thus contribute to the topic of implementing green infrastructure in a systematic or comprehensive manner (cf. the strains of strategic and comprehensive planning). Hedonic results, although partial, provide empirical guidance that identifies less-than-optimal implementations that may hinder other functions of the urban economy, and also indicate solutions that are likely to better harmonize green interventions with a broader array of socio-economic objectives.

The effects of the quantity of green and/or the spatial arrangement of a fixed quantity have not been treated in this study, largely due to the limitation of regression analysis to answer these questions. The main reason for caution against extending the results into such discussions (for instance, do we allocate 1 ha of green into a few large parks, or into several smaller patches) is that the ceteris paribus assumption can be rapidly violated in this context: changing one parameter will in fact cause a change in most other factors, due to the dynamical nature of the system and the scarcity of available land. Nevertheless, while not a complete spatialized account of a city's economy and activities, this analysis confirms that cities are not monolithic organisms (cf. Batty, 2007) and different locations have different economically optimal green solutions, with the empirical information helping towards a more systematic planning of green infrastructure.

The study also explored to some extent the problems stemming from the treatment of temporally aggregate data and from the mixing of pure and spatial spillover effects. The approaches of estimating models in temporal subsets and the approach of separating pure from spatial spillover effects appear to provide clearer and more sensible intuitions; both model alternatives indicate that a large pooled model may have technical merits, but also has the risk of incorrectly estimating coefficients for urban green, or failing to detect significant results altogether. In the case of this study, this was an issue for estimating the marginal effect of distance to a forest; the pooled model is a clear misrepresentation in this respect, even though it estimated the effects of other environmental amenities correctly.

In conclusion, from the viewpoint of sustainable development's original concept of integration, the greening of cities appears to be far from an unconditional goal. Successful spatial solutions must be parameterised according to a few goals: to defining what the location in question is, what green types are considered, and what the intended extent of benefits is. Adding this detail is necessary because, as this study shows, some solutions have surprisingly unintended effects if conceptualized and implemented in the wrong way and wrong location.

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Table 5
Overview of the estimated effects of decreasing distance to urban green.

Effect	*Type of green* FOREST	PARK	FIELD	EFFECT OVERLAPS
Direct	●● ▪ Max. in urban fringe	● ▪ Max. in the CBD	●●● ▪ Max. in urban fringe	▪ >9 km: forest, field
Indirect	●●● ▪ Max. in the CBD	●●● ▪ Max. in the CBD		▪ 0–4 km: park, forest
Total	●●● ▪ Max. in the CBD	●●● ▪ Max. in the CBD	●● ▪ Max. in urban fringe	▪ 0–3 km: forest, park

Notes:
● 0–1% m^{-2}; ●● 1–2% m^{-2}; ●●● 2–3.5% m^{-2}, referring to the price effect of a 100 m change of distance to a green patch.
All kilometre (km) figures refer to distance from the central business district (CBD) of Helsinki, defined as the point of densest commercial establishments within the broader metropolitan region.

Appendix A. Regression estimations

Table A-1
[Spatial error estimation results, biannual samples].

Coef. (std. error)	2010–11	2008–09	2006–07	2004–05	2002–03	2000–01
INTERCEPT	4.919***	5.266***	5.166***	4.647***	4.016***	3.725***
	(*0.094*)	(*0.106*)	(*0.112*)	(*0.107*)	(*0.102*)	(*0.098*)
DEBT/m^2	−0.565***	−0.604***	−0.541***	−0.639***	−0.614***	0.476***
	(*0.014*)	(*0.016*)	(*0.019*)	(*0.034*)	(*0.039*)	(*0.039*)
COST/m^2	−0.019**	−0.018*	−0.021**	−0.031***	0.004	−0.028***
	(*0.007*)	(*0.007*)	(*0.008*)	(*0.005*)	(*0.003*)	(*0.004*)
ROOMS	−0.254***	−0.181***	−0.148***	−0.113***	−0.133***	−0.064***
	(*0.006*)	(*0.006*)	(*0.006*)	(*0.006*)	(*0.007*)	(*0.006*)
AGE	−0.025***	−0.024***	−0.020***	−0.019***	−0.016***	−0.011***
	(*0.001*)	(*0.001*)	(*0.001*)	(*0.001*)	(*0.002*)	(*0.002*)
$[AGE]^2$	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
	(*0.000*)	(*0.000*)	(*0.000*)	(*0.000*)	(*0.000*)	(*0.000*)
FLOOR	0.071***	0.070***	0.076***	0.050***	0.040***	0.049***
	(*0.003*)	(*0.004*)	(*0.003*)	(*0.004*)	(*0.004*)	(*0.004*)
BADCOND	−0.518***	−0.596***	−0.491***	−0.382***	−0.364***	−0.168***
	(*0.028*)	(*0.028*)	(*0.026*)	(*0.030*)	(*0.033*)	(*0.018*)
(AVGCOND	−0.249***	−0.251***	−0.273***	−0.218***	−0.141***	−0.138***
	(*0.012*)	(*0.013*)	(*0.012*)	(*0.013*)	(*0.015*)	(*0.014*)
CBD	−0.120***	−0.270***	−0.269***	−0.221***	−0.173***	−0.191***
	(*0.011*)	(*0.017*)	(*0.019*)	(*0.017*)	(*0.015*)	(*0.016*)
LOTSIZE	0.000·	0.000	0.000	0.000	0.000	0.000
	(*0.000*)	(*0.000*)	(*0.000*)	(*0.000*)	(*0.000*)	(*0.000*)
RLINE	0.110***	0.194***	0.158***	0.100***	0.088***	0.114***
	(*0.017*)	(*0.028*)	(*0.030*)	(*0.028*)	(*0.025*)	(*0.025*)
MLINE	0.088***	0.087***	0.078***	0.075***	0.078***	0.085***
	(*0.008*)	(*0.012*)	(*0.012*)	(*0.012*)	(*0.011*)	(*0.011*)
MJROAD	0.101***	0.154***	0.180***	0.107**	0.026	0.040
	(*0.028*)	(*0.037*)	(*0.039*)	(*0.038*)	(*0.035*)	(*0.038*)
COAST	−0.144***	−0.003	−0.035	−0.040	−0.057*	0.000
	(*0.017*)	(*0.029*)	(*0.030*)	(*0.029*)	(*0.026*)	(*0.026*)
FOREST	−1.097***	−0.269	−1.374***	−1.359***	−0.764*	−1.169***
	(*0.215*)	(*0.360*)	(*0.349*)	(*0.316*)	(*0.339*)	(*0.330*)
FOREST ∗ CBD	0.256***	0.042	0.198**	0.0204***	0.115·	0.186**
	(*0.044*)	(*0.066*)	(*0.062*)	(*0.056*)	(*0.060*)	(*0.063*)
PARK	−0.578***	−0.769***	−0.749***	−0.552***	−0.139	−0.355*
	(*0.129*)	(*0.149*)	(*0.156*)	(*0.149*)	(*0.142*)	(*0.144*)
PARK ∗ CBD	0.059***	0.093***	0.085***	0.065***	0.017	0.048**
	(*0.015*)	(*0.016*)	(*0.017*)	(*0.016*)	(*0.015*)	(*0.015*)
FIELD	0.566***	0.150**	0.138**	0.057	0.050	0.025
	(*0.030*)	(*0.046*)	(*0.048*)	(*0.044*)	(*0.042*)	(*0.041*)
FIELD ∗ CBD	−0.058***	−0.027**	−0.027**	−0.016·	−0.012	−0.020*
	(*0.006*)	(*0.009*)	(*0.009*)	(*0.009*)	(*0.008*)	(*0.008*)
YEAR	0.049***	0.072***	0.163***	0.161***	0.110***	−0.138***
	(*0.011*)	(*0.012*)	(*0.010*)	(*0.011*)	(*0.013*)	(*0.013*)
N	10,839	9532	9330	6513	4755	5013
Pseudo R^2	0.8	0.7	0.7	0.78	0.7	0.67

Notes:
1. Significance ranges: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1.
2. The unit of the ecological independent variables is distance to the green feature in kilometres.
3. The unit of the dependent variable is the property's selling price in € thousand per square meter.

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Housing Prices and the Public Disclosure of Flood Risk: A Difference-in-Differences Analysis in Finland

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Abstract Information gaps and asymmetries are common in the housing market and this is frequently the case with the risks of natural processes, especially in coastal areas where the amenity dimension may dominate the risk aspect. Flood risk disclosure through maps is a policy instrument aimed at addressing this situation. We assess its effectiveness by identifying whether such maps induce a price differential for single family coastal dwellings in three Finnish cities, and by estimating the discount per square meter for various flooding probabilities (return times). The estimations indicate a significant price drop after the information disclosure for properties located in flood-prone areas as indicated by the maps. In the case of sea flooding information in Helsinki, the price effect is sensitive to the communicated probability of flooding. Overall, the discussed policy instrument appears to have functioned as intended, correcting information gaps and asymmetries related to flood risk. The identified effect is spatially selective; it caused a short-term localized shock in market prices in conjunction with some reorientation of demand from risky coastal properties towards ones that represent a similar level of coastal amenity, but are less risky in terms of flooding. This hints at the potential for incorporating the shocks associated with flood events or risk information into broader-scoped urban modelling and simulation. Similarly, the reasonable accuracy with which the housing market processes the additional information shows a potential for wider use of the disclosure of non-obvious risks in real estate markets. In the case of adapting to climate change risks, additional uncertainties may make the disclosure instrument less effective, if used as a single tool.

Keywords Flood risks · Housing market · Information effect · Information gaps

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Introduction

Housing constitutes a complex good that represents a basket of mutually substitutable attributes. Hedonic price estimations are widely used to decompose the price of housing into the marginal values of its traits (Rosen 1974; Dubin 1988; Sheppard 1999; Brueckner 2011). Since the number of attributes can be large, whereas several of them may be hard to measure or evaluate, value attribution can be quite sensitive to incomplete information (Pope 2006, 2008a). Furthermore, information asymmetry between seller and buyer is often the case. This is especially relevant for aspects pertaining to the condition of the house as well as for the practically attainable utility level of various ecological amenities. In many countries, legally underpinned guidelines for disclosure provide buyers some protection regarding the misjudgment of a dwelling's physical condition, but this is much less the case with respect to ecological amenities. Matters get further complicated when some amenities entail merits *and* risks. Waterfront locations, for instance, often have obvious benefits in terms of landscape view, recreation options and so forth. Yet, such locations can be simultaneously subject to flood risks. If the local frequency of damaging floods is quite low (e.g., return times of 50 years or beyond), the buyer—and possibly the seller—is likely to be ignorant about it. Furthermore, even if the buyer is aware of the possibility of floods, that risk may be downplayed, especially if no authoritative information is available.

A perfectly functioning housing market needs full information on external effects, such as noise, industrial hazards, and flood risks, that can affect the quality or duration of a dwelling's housing services. For various hazards the exposure risk of real estate is not self-evident, consequently proper market transparency requires correction for this information gap. Publicly available flood risk maps constitute a policy instrument, which aims at filling information gaps, and the impact of the disclosed risk information should be detectable in the housing market. In this article we examine the effectiveness of publishing spatially explicit flood risk information for real estate by means of flood risk maps. As indicator we use deviations in house prices for otherwise comparable properties after the introduction of the flood risk maps. We construct control and treatment groups in three different cities (Helsinki, sea flooding; Pori and Rovaniemi, river flooding) and employ a difference-in-differences (DD) methodology as the identification strategy. The methodology is implemented via hedonic regression setups, repeated for the three cities and for various flooding frequencies. We compare the outcomes with approximated full information discounts based on engineering-economic information of unit-costs of flooding of real estate in Finland.

Flood Risks in the Housing Market

Flooding and Political Response in Finland

River flooding in Finland occurs regularly, notably during springtime snowmelt. It mostly happens in sparsely populated areas causing rather little economic damage. Larger floods with significant local economic ramifications have been rare. The city of Pori, on the Finnish west-coast, is regarded as the most vulnerable place with respect to river floods in Finland. In the past 100 years flooding occurred in 1924, 1936, 1951, 1974/75, 1981/82 and 2004/05 (Koskinen 2006). In the next few decades, river floods in Pori could cause a direct damage of € 40–50 million at the 2008 protection level, while the direct damage of worst-case situations is estimated from just over € 100 million for F50 floods (return time of 50 years or 1:50 probability) to € 380 million for F250 events (Perrels et al. 2010). In the meantime, Pori has reinforced its embankments, but these efforts covered mainly maintenance backlogs. Rovaniemi, too, is subject to river flood risk, but flooding of the built-up areas has clearly smaller probabilities than in Pori.

Next to river flooding, periodic sea level rise in combination with storm surges can flood various coastal built-up areas. Along the coastline of Helsinki's metropolitan area there are residential pockets that are vulnerable in case of considerable (+2.5 m) sea level rise. In January 2005 flooding occurred in several locations along the coast, including key areas in downtown Helsinki, with costs estimated to approximately € 12 million (Parjanne and Huokuna 2012).

A third type of flooding typically occurs in larger expanses of built-up areas when extreme downpours produce water volumes that cannot be handled by the sewer system, while the predominantly impermeable urban surfaces reduce retention capacity. According to the IPCC Fifth Assessment Report (IPCC 2014, Ch.23) there is high confidence about projected increases in extreme precipitation in Northern and Central Europe. A recent example of what this may imply is the extreme downpour event in Copenhagen on 2.7.2011, which produced 150 mm of rain in 3 h and resulted in approximately € 800 million damage (Gerdes 2012). However, considering the spatial stochasticity of extreme downpours at regional or local scales, the hazards of this phenomenon have not been taken into account in the present analysis.

As a follow-up to the first national adaptation strategy (Marttila et al. 2005), a process was set in motion to review river flooding risks and changes in these risks owing to climate change. At the same time the EU Water Directive (European Communities 2000) stipulated the introduction of flood maps in Member States. As a result, flood risk maps were developed and made available, starting in 2006/7 for a number of flood-prone areas in Finland. They have been accessible to the general public in print and online versions and used in local land use planning and real estate permitting. The maps communicate flood risks in high resolution and spatially explicit form by indicating estimated floodwater heights for floods of several frequencies (Dubrovin et al. 2007; Barneveld et al. 2008; Sane et al. 2008) and most probably improved transparency regarding flood risks for real estate owners and potential buyers.

Risk Information in the Housing Market and Mixing of Risk and Amenity

It is likely that the population in flood-prone areas has been aware of the flood risks, but to a rather varying extent and possibly with misconceptions regarding the intensity and spatiotemporal distribution of the risk. Recent floods have been recorded in the study areas as indicated in Table 1. In Helsinki, the flood in 2005 was much more significant than the 2004 one. Furthermore, the damage potential in Pori is considerably larger than in the other two cities, even more so when normalized per capita. The 2007 flood in Pori, caused by extreme rainfall, induced the highest cost among the listed events.

However, it is known that people make consistent errors in judging and dealing with risk and uncertainty (Tversky and Kahneman 1973, 1974, 1986; Lee et al. 2008),

Table 1 Record of major flood events in the study areas (post-1980)

Greater Helsinki	2004; 2005
Pori	1981; 1982; 2004; 2005; 2007
Rovaniemi	1981; 1993; 2004

Based on data from Silander et al. (2006), City of Pori (2009), and Himanen (2011)

including disaster probabilities (Kahneman and Tversky 1979); this behavior is present in risk discounting by homebuyers, as discussed further on in the text in connection to Figs. 2 and 3. Before 2008, local public authorities had begun commissioning flood risk assessments and identifying possible measures. Yet, this information generally did not seem to have trickled down to the public at large. Furthermore, some municipalities had to reconcile the implications of more restrictive land use guidelines with ambitions to expand residential areas (Peltonen et al. 2006). We also scanned literature—notably 'grey' literature—regarding reports by or for local authorities that may include survey information for the study areas in the period 2004–2008 about home owners' understanding of flood risks to which their property is exposed. To our knowledge no such survey has been held.

Thus, although coarser flood maps were available to some extent before the high resolution maps were published, the issuing of the genuine high resolution flood maps is crucial. This relates to the availability heuristic and its link to salience. People often judge an event's probability by referring to the ease with which such instances can be brought to mind (Tversky and Kahneman 1973: 221) and this type of availability is affected, among others, by salience (Tversky and Kahneman 1974: 1127). It is likely that, although information and data about flooding was formerly available, there must have been something salient about the national response at first, and especially about the high resolution spatially explicit maps showing with precision whether a property is in the floodplain.

The above lead us to hypothesize that owner-occupants of single-family dwellings may be vaguely aware about flood risks in the area, but do not have a clear appreciation of the extent of flood risks to which their property is subjected. As not all waterfront houses are flood-prone, a differentiated effect may be expected if flood risks are accounted for in house prices. This study aims to assess whether the flood risk discount was significantly reinforced or activated after the publishing of flood maps for the relevant urban areas. The default is that owner-occupants of dwellings outside the designated flood risk areas think that there is no risk, whereas those inside the designated flood contours tend to only mildly deviate from this default assumption – perhaps with the exception of those at actual shore locations. An exception is made for Pori, where river flood risk awareness had been much higher over the past century.

Two additional issues are relevant. Firstly, information effects related to environmental changes or urban planning and policy decisions have been often estimated in the housing market (Kiel and McClain 1995; Pope 2008a, b). However, information effects decay. McCluskey and Rausser (2000) and McCluskey (1998) raise the distinction between short and long term effects in the housing market and discuss estimation techniques that are appropriate for the detection of either case. This connects to evidence that flood risk awareness and/or perception tend to deteriorate over time (Atreya et al. 2013; Bin and Landry 2013), but also to the phenomenon that in communities with high renewal rate of residents the decay can be even quicker due to the disruption of pre-established social networks upon which risk awareness relies (Kasperson et al. 1988; Scherer and Cho 2003).

Publicly accessible, high quality flood maps were not available before 2008 for Greater Helsinki and Rovaniemi. Furthermore, the morphology of the flood prone areas is strings of scattered pockets of flood prone locations rather than a continuous (and obvious) flood plain. In addition, parts of the affected built-up areas were developed relatively recently. We therefore assume that awareness about flood risks in Greater Helsinki and Rovaniemi was moderate at best. Another complicating factor may be that, notwithstanding a relatively high awareness of flood risks, sensitivity to flood risks may have deteriorated depending either on time or recovery perception. In the case of Pori, which has an evident and publicly known flooding history, it is not unlikely that many homeowners have at least some awareness about flood risks of their property. However, the most recent serious floods date from 1981/82 (Perrels et al. 2010) with modest damage impact, and from 2007 with extensive flooding, but unrelated to river/sea flooding (an exceptional multi-cell cluster storm).

Secondly, while waterfront-related amenity effects (e.g., Leggett and Bockstael 2000; Conroy and Milosch 2011; Votsis 2014) and the impact of occurred floods or of flood risk levels (e.g., Harrison et al. 2001; Bin and Polasky 2004; Lamond 2008) are often estimated, it is frequently overlooked that amenity- and risk-related marginal effects may be mixing into each other as they originate from the same physical feature. Daniel et al. (2009) provides a quantitative meta-analysis of key previous studies on the topic. He points out that while the empirical evidence does indicate that housing prices are affected by flood risks, the main problem is the mixing of the amenity and risk effects associated with proximity to the waterfront. Bin et al. (2008a, b) are examples of estimating the response of the housing market to both the amenity and risk dimension of the waterfront. We expect this mixing to be present in estimating the effects of information release about risk levels.

Identification Strategy

We employ a difference-in-differences approach (Card and Krueger 2000; Angrist and Pischke 2009; Huttunen et al. 2013) to capture the price differential of flood risk disclosure. The treatment group is defined as those dwellings that are located in the flood prone area, and the control group as dwellings that are nearly identical to and in the vicinity of the treatment group, but not in the flood prone area. The pre-treatment cases are transactions in the treatment group that took place before the introduction of the flood risk maps, whereas the post-treatment cases include the transactions that were realized after the introduction. The key identifying assumption is that the treatment and control groups have had parallel price trends during the studied timeframe, as well as identical underlying price formation and differentiation mechanisms.

Let s and t be group and time indices, respectively, and consider the following cases: $s=CONTROL$ for transactions in the control group; $s=TREAT$ for transactions in the treatment group; $t=BEFORE$ for the time period before the policy change (public disclosure of the flood risk maps); $t{=}AFTER$ for the time period after the policy change. Furthermore, denote P_{0ist} as the price in group s and time period t where no policy change has happened, and P_{1ist} as the price in s and t where the policy change has happened. The baseline no-treatment state is $E[P_{0ist} \mid s, t]=\gamma_s+\lambda_t$, to which an additive structure of case-specific differences is introduced. Let D_{st} be a dummy for the policy change, so that if we assume that $E[P_{1ist}-P_{0ist} \mid s, t]$ is a constant, denoted by δ, then the dwelling's price is $P_{ist}=\gamma_s+\lambda_t+\delta D_{ist}+\varepsilon_{ist}$, with $E[\varepsilon_{ist} \mid s,t]=0$. From here, we get a before-and-after effect for each of the two groups, namely:

$E[P_{ist} \mid s{=}CONTROL,\ t{=}BEFORE]-E[P_{ist} \mid s{=}CONTROL,\ t{=}AFTER]=\lambda_{BEFORE}-\lambda_{AFTER}$, which is the price differential for the dwellings outside the floodplain (control group) for before and after the policy change, and

$E[P_{ist} \mid s{=}TREAT, t{=}BEFORE]-E[P_{ist} \mid s{=}TREAT, t{=}AFTER]=\lambda_{BEFORE}-\lambda_{AFTER}+\delta$, which is the respective price differential for the dwellings inside the floodplain (treatment group).

Note that due to the identifying assumption, the terms λ_{BEFORE} and λ_{AFTER} are identical for the two above cases. The population difference-in-differences would then be:

$$\{E[P_{ist} \mid s = CONTROL,\ t = BEFORE]-E[P_{ist} \mid s = CONTROL,\ t = AFTER]\}-\{E[P_{ist} \mid s = TREAT,\ t = BEFORE]-E[P_{ist} \mid s = TREAT,\ t = AFTER]\} = \delta,$$

in which δ is the causal effect of interest. This additive set-up is estimated in a linear regression framework. A set of j group-invariant attributes X is added that corresponds to hedonic characteristics, so that the final form of the empirical specification is:

$$P_{ist} = \alpha + \gamma TREAT_s + \lambda AFTER_t + \delta(TREAT_s{*}AFTER_t) + \sum X_{istj}\beta_{istj} + \varepsilon_{ist}, \quad (1)$$

where γ is the general effect of being in the floodplain without controlling for time, λ is the general time trend in the price of all the dwellings, and δ is the aforementioned effect of the public disclosure of flood risk maps.

Study Areas and Data

The study areas, predominantly residential built-up areas, are shown in Fig. 1. As an indication of the spatial morphology of the analyzed flood risks, the maps also show the flood zone of an F1000 event. Three cases were estimated: sea flood risks in Greater Helsinki; river flood risks in Pori; and river flood risks in Rovaniemi.

The study uses entries from a large real estate transaction dataset, voluntarily collected by a consortium of Finnish real estate brokers and refined and maintained by the VTT Technical Research Centre of Finland Ltd. As not all real estate agencies participate, the dataset represents a sample (albeit rather large) of the total transaction volume. The records include the selling price, debt component, maintenance cost,

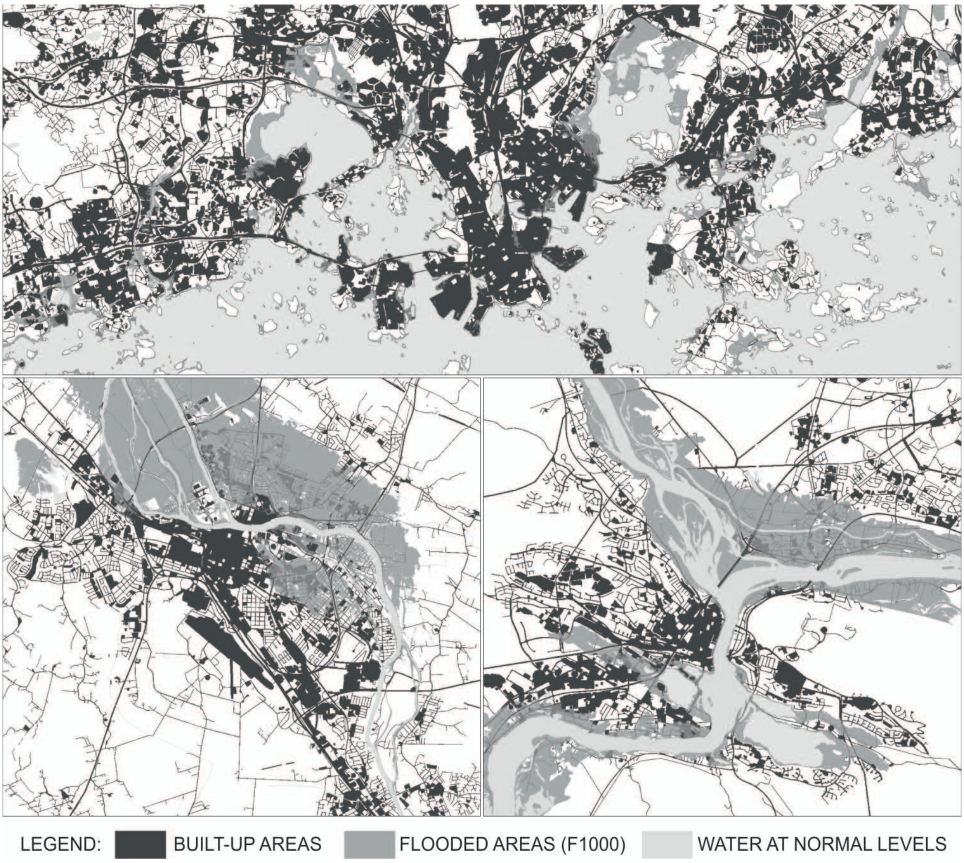

Fig. 1 Study areas: top: Helsinki; bottom left: Pori; bottom right: Rovaniemi

postal address, listing details (date listed and sold), and structural attributes of sold dwellings in selected Finnish cities during 1971–2011. The acquired data were subsequently geocoded and converted into a GIS database by the authors. Based on the coordinates, neighborhood and environmental attributes were added for a subset covering the period 2000–2011. The price, debt, and cost were de-trended by adjusting for inflation with 2011 as the base year. Subsets of this final database are utilized in the present analysis.

A procedure was followed to select samples of detached single family dwellings and ground-floor terraced (row) houses, situated near the river bank or sea coast. It aimed at producing homogenous samples for treatment and control groups. The sample was delineated by selecting dwelling transactions inside the flood risk areas plus transactions inside a buffer zone around the flood risk areas. The buffer size was set to 300 m for Greater Helsinki and Rovaniemi, and 600 m for Pori (due to the large flood risk area in comparison to the other two urban areas). The examined flood frequencies were F5, F10, F20, F50, F100, F250 and F1000. The numbers represent occurrence probabilities per year, such that F5 refers to a 1:5 probability and F1000 to a 1:1000 occurrence probability per year.

Table 2 shows averages for the variables 'price per square meter' (PRICE/m^2), 'floor-space' (FLOORSPACE) and 'number of days the property was on sale' (ONSALE) by DD group (2×2) for the indicative flood frequency of F250.

Table 2 Mean values of key variables per difference-in-differences group for F250

		Greater Helsinki		Rovaniemi		Pori	
		BEFORE$_t$	AFTER$_t$	BEFORE$_t$	AFTER$_t$	BEFORE$_t$	AFTER$_t$
PRICE/m^2 (€ thousand, 2011 prices)	CONTROLF_f:	2.98	3.53	1.26	1.5	0.93	1.48
	TREATF_f:	2.94	3.25	1.38	1.37	1.04	1.2
FLOORSPACE (m^2)	CONTROLF_f:	123.28	120.04	86.16	91.27	127.02	116.64
	TREATF_f:	111.8	118.61	86.74	93.07	121.13	120.96
ONSALE (days from listed to sold)	CONTROLF_f:	81.05	72.99	58.7	55.7	95.02	92.03
	TREATF_f:	101.31	150.55	86.66	83.63	92.5	99.17

Sample sizes (out of parenthesis: total, in parenthesis: AFTER$_t$): Helsinki: $N_{CONTROL}$: 204 (82), N_{TREAT}: 73 (38); Rovaniemi: $N_{CONTROL}$: 660 (181), N_{TREAT}: 155 (51); Pori: $N_{CONTROL}$: 54 (29), N_{TREAT}: 325 (164)

While there is a general price increase in both the control and treatment groups when comparing average prices per group in the years prior and after the risk disclosure (differences between time groups), the increase is systematically lower in the treatment group as compared to the control group (difference-in-differences). The selected houses have similar average sizes for the control and treatment groups per period, except in the 'before' period in Helsinki where the average floor space of sold houses in the control group is somewhat larger. There are no systematic trends in the sizes of the sold houses.

The floor space information is otherwise interesting as a rough indication of typical total discount per house after the flood risk disclosure. This could be compared to other physical cost estimates of flood damage in houses; such a calculation is provided at the end of section 5. Changes in average floor space are also relevant for interpreting the observed changes in prices per m^2 (for similar types of homes increases in floor space are usually accompanied by reductions in price per m^2).

The ONSALE parameter is added to infer whether the treatment group largely followed market sentiments or—conversely—whether selling in the treatment group seemed to be harder (i.e., longer time 'on sale'). The houses of the treatment groups in Greater Helsinki and Pori exhibit an increase in the average time on sale, while the houses in the control group tend to be sold faster than in the 'before' period, notably in Helsinki. On the other hand, the time on sale in Pori does not differ much between the groups, neither before nor after the introduction of the flood maps. The significant increase in time being on sale in Greater Helsinki suggests increased difficulties to sell the houses of the treatment group at the intended price. Sellers in the control group may have benefitted from the situation (see section 7 on policy discussion). Table 3 provides an overview of the rest of the variables in the dataset.

Estimation and Testing

Equation 1 was estimated as a DD hedonic regression, using price per square meter as the dependent variable and the variables of Table 3 as the independent variables, with slight variations in the regression specification of each urban area due to differences in

Table 3 Independent variables and mean values

Variable	Description	Urban area		
		Greater Helsinki	Rovaniemi	Pori
COST/m^2	Debt[a] plus regular maintenance per m^2 (€, 2011 prices)	.12	.14	.001
REGUNRATE	Regional unemployment rate (monthly%)	5.88	12.34	8.15
AGE	Age (years)	28.76	19.06	33.73
AVGCOND	Average condition (binomial: 1=AVG; 0=otherwise)	.16	.03	.21
BADCOND	Bad condition (binomial: 1=BAD; 0=otherwise)	.02	.03	.09
CONDITION	Condition (multinomial.: 0=BAD; 1=AVG; 3=GOOD)	2.79	2.9	2.61
ROOMS	Number of rooms, excl. kitchen (multinomial: 1–9)	4.07	3.11	3.48
CBD	Distance to the city center[b] (m)	9248	3371	2836
SEA	Distance to the sea coast (m)	253.4	–	–
RIVER	Distance to the riverfront (m)	–	751	792
LAKE	Distance to the lakefront (m)	–	679	–
ESPOO	Located in Espoo suburb (binomial: 1=Espoo; 0=Helsinki)	.37	–	–
TREAT*Ff*	Dummy for the treatment group. 1 indicates situation inside a floodplain with flooding frequency *Ff*, where *f*={5; 10; 50; 100; 250; 1000}, 0 otherwise			
AFTER*t*	Dummy for the post-treatment cases; 1 indicates transactions after the policy change, 0 otherwise			

[a] A debt component arises due to large maintenance costs (e.g., roof change, structural renovations) for properties situated under a common roof (i.e., row or other semi-detached houses). Such technical work is managed by a housing committee and funded by a common loan, which is then distributed to individual properties

[b] In the case of Greater Helsinki (Helsinki and Espoo in this sample), CBD refers to the center of Helsinki

the local market and built environment. A few objects with very high prices were excluded from the sample, as these may lead to overstatement of the discount effect. The estimations are given in Tables 4 (Greater Helsinki) and 5 (Rovaniemi and Pori).

Overall, the effect of being located in the risk areas with no control for the time of the policy change (TREAT*Ff*) is in most cases a price premium, but not always statistically significant. The effect changes into a statistically significant price discount when controlling for after the policy change (TREAT*Ff* * AFTER*t*). The general trend (that is, without controlling for group effects) between the before and after period (AFTER*t*) is a price increase, as was shown already in Table 2. Group-invariant controls for proximity to water bodies in each city are taken as amenity estimators, and appear to have statistically significant premiums. A notable observation is that the price discount's magnitude in the case of sea flooding in Greater Helsinki is dependent on flooding frequency. These elements are described in more detail below.

In Greater Helsinki (Table 4) the introduced maps concern regular sea flooding zones under current climate conditions. The effect of the information change on prices is statistically significant for the events F5 to F1000. Location in the various risk areas with no control for time has a statistically insignificant effect. The group-invariant term

Table 4 Estimated price effects in Greater Helsinki (sea flooding)

Parameter	Coefficient (*std. error*)						
	F1000	F250	F100	F50	F20	F10	F5
Group-dependent							
AFTER*t* [*t*=28.6.2007]	.678***	.675***	.657***	.637***	.624***	.626***	.617***
	(.0944)	(.0965)	(.0917)	(.09)	(.0925)	(.0837)	(.0834)
TREAT*Ff*	–.147	–.125	–.144	–.235·	.27	.325	.307
	(.111)	(.128)	(.132)	(.14)	(.245)	(.279)	(.301)
TREAT*Ff* * AFTER*t*	–.373*	–.428*	–.354·	–.316·	–.882**	−1.0607**	−1.0498**
	(.163)	(.182)	(.183)	(.188)	(.313)	(.353)	(.37)
Group-invariant							
INTERCEPT	13.89***	13.89***	13.63***	13.55***	13.83***	13.88***	13.95***
	(1.256)	(1.319)	(1.275)	(1.258)	(1.341)	(1.3)	(1.301)
COST/m^2	–.503**	–.478**	–.495**	–.48**	–.408*	–.568***	–.585***
	(.16)	(.166)	(.162)	(.158)	(.175)	(.163)	(.161)
AGE	–.0187**	–.0182*	–.0189**	–.0181*	–.0119	–.0268***	–.0267***
	(.00689)	(.00719)	(.0071)	(.00697)	(.008)	(.00759)	(.00748)
$[\text{AGE}]^2$	.00025*	.000253*	.000254*	.00025*	.00018	.00037**	.00036**
	(.0001)	(.00011)	(.0001)	(.0001)	(.00012)	(.00011)	(.00011)
REGUNRATE	–.197**	–.207**	–.190**	–.194**	–.193*	–.208**	–.212**
	(.068)	(.0722)	(.0693)	(.0678)	(.0748)	(.0702)	(.0694)
ROOMS	–.0971**	–.108**	–.104**	–.0996**	–.118**	–.0954**	–.0886**
	(.0333)	(.0356)	(.0339)	(.0332)	(.0383)	(.0341)	(.0337)
CONDITION	.332***	.335***	.314***	.326***	.385***	.304***	.313***
	(.085)	(.089)	(.0861)	(.0852)	(.0978)	(.0867)	(.0865)
ESPOO	.617***	-.628***	.605***	.538***	.569***	.657***	.637***
	(.109)	(.116)	(.113)	(.113)	(.118)	(.113)	(.113)
log [CBD]	−1.021***	−1.013***	–.991***	–.974***	−1.032***	−1***	−1.008***
	(.135)	(.142)	(.136)	(.136)	(.144)	(.137)	(.138)
log [SEA]	–.183***	–.183***	–.181***	–.196***	–.185***	–.187***	–.191***
	(.0375)	(.0387)	(.0383)	(.0379)	(.0431)	(.0417)	(.0414)
N_{CONTROL}	204 (82)	204 (82)	226 (91)	231 (92)	237 (93)	277 (117)	282 (118)
N_{TREAT}	95 (47)	73 (38)	68 (37)	62 (36)	22 (14)	17 (11)	16 (11)
mult. R^2	.400	.397	.388	.400	.392	.380	.379

1. The dependent variable is price per m^2 (in EUR thousand)

2. Significance levels: ***<.000; ** .001; * .01; · .05

3. Number of observations (*N*): outside parenthesis: total; in parenthesis: AFTER_t

of coastal distance (log [SEA]) captures a highly significant amenity premium, which presumably explains the insignificance of the TREAT*Ff* term in this case. In other words, this means that the amenity premium effect of near waterfront locations works basically the same for both treatment and control groups. After the map introduction,

Table 5 Estimated effects in Rovaniemi and Pori (river flooding)

Parameter	Coefficient (*std. error*)				
	Rovaniemi F1000	Rovaniemi F250	Pori F250	Pori F100	Pori F50
Group-dependent					
AFTER*t*	.167***	.163***	.228**	.231**	.218**
	(.0238)	(.0238)	(.0729)	(.0731)	(.068)
TREAT*Ff*	.0922***	.104***	.0927	.101	.135*
	(.0244)	(.0295)	(.0629)	(.0643)	(.0586)
TREAT*Ff* * AFTER*t*	–.0822*	–.105*	–.128·	–.131·	–.116·
	(.0393)	(.0485)	(.0745)	(.0748)	(.0698)
Group-invariant					
INTERCEPT	3.789***	3.927***	1.712***	1.708***	1.637***
	(.202)	(.215)	(.142)	(.144)	(.142)
COST/m^2	–.747***	–.779***	11.625	12.057	11.611
	(.0291)	(.0318)	(9.813)	(9.818)	(9.872)
AGE	–.0217***	–.0232***	–.0178***	–.0195***	–.0178***
	(.00192)	(.00207)	(.00173)	(.00186)	(.00179)
$[AGE]^2$	.000138***	.000164***	.000128***	.000153***	.00013***
	(.0000328)	(.0000355)	(.000018)	(.00002)	(.000018)
REGUNRATE	–.0733***	–.0753***	–.0330**	–.0306*	–.0317*
	(.00423)	(.0045)	(.013)	(.0128)	(.0131)
ROOMS	–.0257***	–.022**	–.0204**	–.0199**	–.0203**
	(.00637)	(.0068)	(.00752)	(.00763)	(.00783)
AVGCOND	–.254***	–.259***	–.148***	–.149***	–.144***
	(.0468)	(.0487)	(.036)	(.0366)	(.0368)
BADCOND	–.0177	–.00524	–.403***	–.382***	–.395***
	(.0486)	(.0519)	(.0489)	(.052)	(.0509)
log [CBD]	–.12***	–.135***	–	–	–
	(.0238)	(.0245)	–	–	–
LAKE	–.000069***	–.0000639**	–	–	–
	(.0000191)	(.0000208)	–	–	–
RIVER	–.000069***	–.0000642***	.00005·	.000044	.000078*
	(.0000115)	(.0000118)	(.00003)	(.000031)	(.000031)
$N_{CONTROL}$	660 (181)	660 (181)	54 (29)	54 (29)	65 (33)
N_{TREAT}	257 (93)	155 (51)	325 (164)	314 (154)	294 (149)
mult. R^2	.611	.609	.583	.573	.587

1. $AFTER_t$ for Rovaniemi: 23.6.2009; $AFTER_t$ for Pori: 11.2006

2. The dependent variable is price per m^2 (in EUR thousand)

3. Significance levels: *** <.000; ** .001; * .01; · .05

4. Number of observations (*N*): outside parenthesis: total; in parenthesis: $AFTER_t$

location in the flood prone areas incurs a statistically significant discount in the range of € 316–1060 per square meter, depending on flooding probability. The price increase in the entire sample from the period before to the period after the policy implementation is estimated to be in the range of € 617–678 per m^2; this increase of the overall price level in the sample is over and above inflation as the analysis has used de-trended prices.

Pori and Rovaniemi (Table 5) are both medium-sized cities with residential areas prone to river flooding. Different levels or different types of awareness regarding flood risks may prevail in the two cities. In Pori the baseline level of awareness about flood risk is likely to be higher than in Rovaniemi due to the frequency of floods and flood damages. Alternatively, even though river floods do occur regularly in Rovaniemi, they usually do not threaten the built-up area (hence the availability of flood maps for high return times only). To some extent the situation in Rovaniemi could be pictured as 'denial' or 'down playing'. Interestingly, the resulting price corrections in Pori in percentage terms are larger than in Rovaniemi. The coefficient of TREAT*Ff* is estimated to € 110 per square meter on average in Pori, and to € 98 per square meter on average in Rovaniemi. Regarding the price effect of the released flood risk information, we observe an average price discount of € 94 per m^2 in Rovaniemi after the map introduction, and of € 125 per m^2 in Pori. There is some variation of the discount among the different flood frequencies in each city, but from the estimations no evident sensitivity regarding occurrence frequencies can be inferred.

Although the estimated discounts differ across the three areas when expressed in €/m^2, they tend to converge when normalized by the average price/m^2 of the corresponding AFTER*t* group. The normalized discounts converge to approximately 10 to 13 % of the average post-treatment price per square meter in Greater Helsinki and Pori, whereas in Rovaniemi they hover between about 6 and 8 %. The exception is the higher-frequency events in Helsinki, where the discount is approximately 25 to 30 % of the average post-treatment price.

Concerning the group-invariant parameters, the coefficients are as expected in routine hedonic regressions. Increased distance to the city center (log [CBD]) returns a strong exponential price drop. Notably in Greater Helsinki, a similar exponential price drop with increased distance from the sea cost (log [SEA]) remains important even in this limited sample of all-coastal properties. Increasing the property's age (AGE) discounts price, until historical status steps in ($[AGE]^2$). The negative sign of the coefficient for rooms (ROOMS) follows from the price/m^2 unit of the dependent variable and indicates the diminishing marginal utility of additional units of space. Departure from good condition toward bad or average (BADCOND, AVGCOND) discounts price, and properties in Helsinki's suburb of Espoo (ESPOO) are more expensive than those in Helsinki, controlling for distance to the metropolitan CBD. Lastly, rising unemployment rate (by urban region), seen as a general indicator of the broader macroeconomic context, reduces unit price. Other frequently estimated hedonic attributes are absent due to sample homogeneity.

The sensitivity of Helsinki's estimated effect (TREAT*Ff* * AFTER*t*) to flood frequency is of interest. Figure 2 plots the information effect with estimation uncertainty, and the normalized effect per average price/m^2 against the corresponding flood probabilities. Although the estimated numbers have to be understood as *indicative* responses to flood risk information, it is evident that the discount is not constant, and that it exhibits a nonlinear relationship to event probability. The discount is larger for the most probable events (5- to 20-year

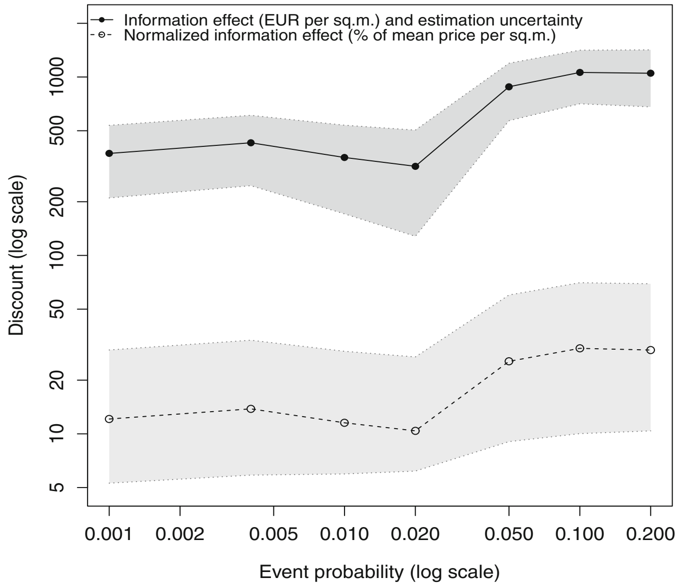

Fig. 2 Sensitivity of the information effect to sea flooding frequency, Greater Helsinki

floods) and drops sharply from approximately € 1000/m^2 in the 10-year flood prone areas to approximately € 320/m^2 in the 50-year areas.

This could be a pseudo-sensitivity and represent the fact that the discount follows the total price of the properties that are also closer to the coast (where floods might be more frequent, but not necessarily, due to other factors such as soil mechanics and topography). However the price discount is expressed in price change per m^2, which to some extent already neutralizes the pronounced rises in the total value of properties nearer to the coast. In order to further neutralize the possible effect of pronounced price rises, the price discount per m^2 is divided by the average price per m^2 of the considered houses (the lower dotted line in Fig. 2). Apparently after this neutralization the sensitivity to occurrence probability remains. Lastly, the DD setup has been estimated with a separate control for coastal proximity (log [SEA]) and with additional controls for potentially interfering hedonic attributes. The estimated effects of the controls do not differ substantially between flood frequencies. For the above reasons, it appears that the discussed dependence can be interpreted as a real sensitivity of the market to different flood frequencies, over and above proximity to the coastline, property value, and other interfering hedonic attributes.

A discount that rises sharply when moving from the group of low frequency events (F1000 to F50) towards that of high frequency events (F20 and beyond) could be rational if it relates to the expected duration and disruptions of the flow of services provided by housing. To explore this assumption, we looked firstly at residential mobility patterns in the Finnish housing market, and secondly at a possible correspondence of the discount rise with similar rises in expected monetary damage.

Exact figures on average homeownership duration for single family and semi-detached dwellings are not available, but cautious approximations can be made based on available reports and the analyzed sample. Finland displays the 6th highest residential mobility rate among OECD countries (Caldera Sánchez and Andrews 2011), which is corroborated by descriptive statistics of the present sample: the average resale time is 3.4 years in Greater Helsinki, 3.8 years in Pori, and 3.4 years in Rovaniemi. This gives sense to Fig. 2, as shorter tenures agree with the evidence that buyers treat damage threats that repeat roughly every 2 to 20 years more seriously than those events beyond the 50-year time horizon.

The bounded-rational behavior indicated by Fig. 2 also echoes elements of prospect theory. In particular, people tend to either ignore or overweigh highly unlikely events, while the distinction between certainty and high probability is either neglected or exaggerated (Kahneman and Tversky 1979: 282–283). In other words, people exhibit biases and mistakes in coping with either end of the probability range. On one hand, this would suggest for Fig. 2 that the group of high frequency events is overstated, while that of low frequency events is understated, explaining the nonlinear differences in the discount curve. On the other hand, it would also suggest that high probability events are practically merged in a single “certain” group, explaining the sharp rise of the estimated discount after the F50 event.

Next, we checked whether the expected monetary damage for a typical dwelling displays a similar dependency on flooding probability. It was assumed that prospective buyers may operate with time horizons of 20, 30, or 40 years in mind when discounting expected flood damage. Monetary damages per square meter for Finnish dwellings (excluding apartments) per floodwater depth group were retrieved (Michelsson 2008, cited in Perrels et al. 2010: 65). Since these unit costs refer to floodwater depths, they were translated to indicative unit costs for different flooding probabilities, based on an assumed connection of flood frequency to floodwater depth for a given location. The unit costs were then multiplied by the average floor space of 121 m^2 and by the probability of having at least one flooding event for each of the assumed time horizons, in order to produce expected flood damage costs for typical properties in the study area for the mentioned horizons.

The results (plotted in Fig. 3) indicate a sharp rise in the expected damage costs as the flooding events become more probable. Notably, in the range of the F100-F50 events there is a reversal of the rising trend into a slight decrease of cost, which resembles the decrease of the estimated risk discount in Fig. 2 for the F250-F50 event range. Similarly, the two figures agree that from F10 to F5 the increase in expected damage cost and in estimated risk discount slows down. The resemblance in those two elements becomes more pronounced as the assumed time horizon increases. The similarity between Figs. 2 and 3 renders it plausible to hypothesise that the estimated information shock is intrinsically connected to the manner in which prospective buyers assess likely damage costs over a multi-year time frame. Figs. 2 and 3 represent notably different methodologies; the former captures market response to disclosed risks, while the latter reflects calculations of technical damage costs from an engineering perspective. Their similarity serves as an additional indication that the estimated price differentials and sensitivity to flood probability are correctly identified. Furthermore, it indicates that the real estate market incorporates the extra information fairly accurately, but this is limited by biases and errors in uncertainty and risk assessment. If we compare the results at face value, the message would be that the price discounts in the market are larger than the approximated expected value of the damage, which adds to the distortion of the response to very high or very low probabilities discussed earlier. Yet, it should be emphasized that the engineering-economic calculations are rather

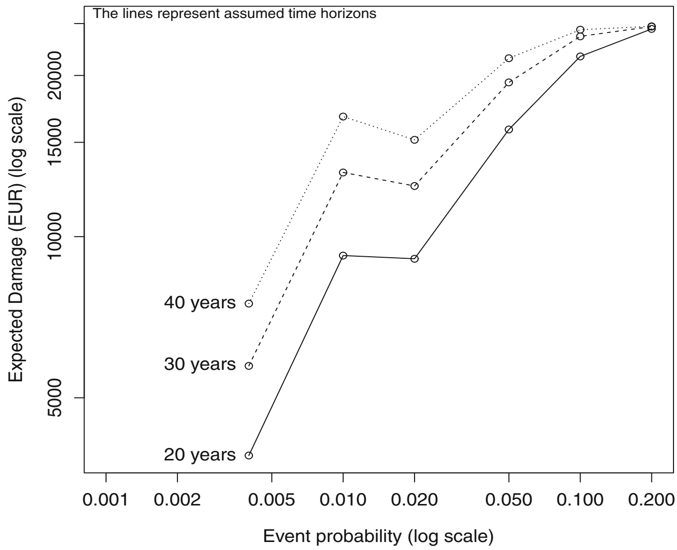

Fig. 3 Expected flood damage for a typical dwelling in Greater Helsinki's coast by return time

generic, and by no means specifically meant for the considered houses. For example, other assumptions on the distribution of water depths over return times of floods can easily increase the costs, but the shape of the curve remains largely the same.

Two additional assumptions about the detected sensitivity are relevant. Firstly, the flood risk maps might have had a "confrontational" effect concerning the risk differential of otherwise similar dwellings: coastal properties exposed to frequent flooding threat re-evaluated against properties with comparable coastal amenity benefits but exposed to less a frequent threat. Secondly, buyers may react stronger to high probability or frequency than to anticipated flood water height (less frequent, but potentially with deeper floodwater). Nevertheless, more analysis is needed to sort out the behavioral aspects that underlie the discussed sensitivity, including the question of whether the economic agents have reacted in this case to flooding frequency, probability of damage, or a combination of the two.

Counterfactual Testing

The identifying assumption of DD methodology is obviously a strong one, especially when the effects are estimated on rather volatile time series such as housing prices. Volatility may entail semi-permanent jumps in housing prices, which would be hard to distinguish from a treatment effect, and for the present estimation context this means relaxing the assumption of perfectly parallel trends between the control and treatment groups, as well as the expectation of finding a textbook DD effect. Non-stationarity is another common characteristic of housing prices, and, while not necessarily associated with volatility, this type of process can produce time series that pose similar challenges to the clear-cut expectations of DD methodology.

To rule out the possibility that the captured effects are temporal artefacts, three sets of checks were carried out. Firstly, we constructed two different control groups for the treatment group of each flood zone. In the first case, observations that fall in one flood zone but not in the next are moved from group TREAT to group CONTROL when doing estimation for the next flood zone. In the second case, instead of swapping directly between CONTROL and TREAT, observations that are first in TREAT but out of TREAT in the next (higher frequency) zone are set aside for one step and only enter the CONTROL group in the second next step. The argument for this alternative approach is that owners may think they are still dangerously close to the zone, even though not literally in it. This is not necessarily a strictly rational behavior, but would concur with the idea that aspirant home-owners use the maps as indicative of flood risks, but do not strictly apply the numbers from the maps, or conversely they are cautious and add a margin. In both approaches of group assignment, the regressions yielded very similar results; the preceding sections report the estimations of the latter TREAT vs. CONTROL case. Secondly, we ran validation regressions in which the specifications of Tables 4 and 5 were repeated with a randomized year of map introduction (variable AFTER*t*) within the timeframe of the transactions. These test regressions returned no consistent results for the term of interest (TREAT*Ffh* * AFTER*t*), which suggests that the captured effect is not a random temporal artefact. In addition, the time of map introduction was different for each of the three study areas, and capturing a similar effect independently for each urban area is further indication against temporal randomness. Thirdly, high-price outliers were excluded from the sample. This, in combination with the estimation in per-square-meter units, ensures that the estimated effects reflect the majority of properties, and are not skewed by the excessive values and risk discounts of a few high-priced outliers.

Another possible interference is the financial crisis that started at the end of the previous decade, roughly at the time that the maps were published. We are confident that the financial crisis has a degree of market penetration that makes it difficult to expect that the control group would be affected differently than the treatment group in a rather homogeneous sample, when both groups are essentially the same kind of properties, mixed at the same location (flood risk areas are irregular patches of land). In other words, we have a strong case that the treatment and control groups differ only in whether they were influenced by the flood risk information or not. In addition, we have controlled for the broader macroeconomic conditions by including the regionally disaggregated unemployment rate for each study area. If the captured effect was misidentified with the effect of the financial crisis, the unemployment control should have picked that up and would have disrupted the estimations, but no such problem was present.

In summary, identifying shocks in the housing market that coincide with a broader economic depression is obviously a difficult issue for DD methodology, as is the use of volatile time series. In both cases, the limitations of the DD methodology are evident, and we caution that the inclusion of additional temporal or macroeconomic controls move beyond the original expectations or capacity of both DD and hedonic estimation.

Policy Discussion

Urban policy and planning actions often induce shocks in the housing market, as in the case of new zoning legislation or other land use controls, transportation system modifications, local economic development decisions, or changes in environmental protection and natural hazard regulations. From a temporal perspective, the shocks can be short-run and/or long-run effects, and while both types affect the equilibrium, the analysis of direct transaction prices—employed in this paper—measures immediate short-run shocks, whereas long-run changes are measured in the evolution of housing price appreciation indices (McCluskey 1998; McCluskey and Rausser 2000). There are indications in the PRICE/m^2 and ONSALE statistics of the sample that the identified effect did not wear off in the years following the risk disclosure, but the evidence is inconclusive due to sample size and the lack of a longer time frame in the observations.

Some information about the spatial character of the policy tool can be identified by expressing Eq. 1 as a spatial regression specification. In this case, the spatially lagged transformations of the dependent and independent variables were included as right-hand variables in Eq. 1 by letting the first-order von Neumann neighborhood define the spatial weights matrix, and the resulting model was estimated in a maximum likelihood framework (Anselin 1988; LeSage and Pace 2009). The estimation and spatial impacts simulation separated the information effect into a statistically significant direct impact and statistically insignificant indirect and total impacts. Borrowing from LeSage (2008), direct impacts can be seen as effects on a typical region that are induced by a policy change in the same region, indirect are effects on a typical region induced by a policy change in neighboring regions, while total are effects on a typical region induced by a simultaneous policy change in all regions in a regional system. Thus the fact that the impacts simulation returned significant coefficients only for the direct category can be taken as an indication that the detected shock functioned as a spatially selective policy instrument in the three urban areas to which it was applied.

Combining the aforementioned temporal and spatial characteristics, it is reasonable to associate the identified information effect as a location-selective, short-run shock in the housing market. This is relevant to climate change adaptation policy as the building blocks of such policies do include information (e.g., flood maps, risk awareness) in addition to attenuation (e.g., green roofs, ‘soft areas’, elevated constructions, water resistant materials) and protection (e.g., dikes). The results suggest that measures such as the information component of an adaptation policy that are softer than more traditional tools like zoning, legislation or taxation can be as effective and can have a measurable influence on housing prices. From an urban planning point of view, such location-selective information policies can be considered as “informational zoning”. However, more elaborate spatiotemporal models have to be estimated on a longer and more populous time series than what was available for this study in order to be able to understand additional spatial and temporal details of this particular policy instrument.

Lastly, the group comparison of variables PRICE/m^2 and ONSALE of Table 2 was extended to include transactions that are unrelated to the treatment and control groups, but represent same type dwellings for the rest of the city (Table 6). The statistics show that the control group stands out in terms of decrease in the time on sale and of increase in price in the period after the map publication. Thus, the suggestion arises that the control group has benefited from a reorientation of demand from waterfront-but-risky to waterfront-but-less-risky or almost-waterfront-but-less-risky properties.

The evidence of demand re-orientation towards less risky coastal properties, the statistically significant price differential in flood-prone properties, and the fact that properties in the higher probability flood zones experienced a noticeably higher discount in comparison to those in lower probability flood zones, cumulatively suggest

Table 6 Indications of demand re-orientation to less-risky coastal dwellings

		Greater Helsinki			Rovaniemi			Pori		
		BEFOREt	AFTERt	% change	BEFORE*t*	AFTER*t*	% change	BEFORE*t*	AFTER*t*	% change
PRICE/m^2 (€ thousand, 2011 prices)	CONTROL*Ff*:	2.98	3.53	18.5	1.26	1.5	19.1	0.93	1.48	59.1
	TREAT*Ff*:	2.94	3.25	10.5	1.38	1.37	–.7	1.04	1.2	15.4
	REST OF CITY:	2.62	3.03	15.7	1.28	1.47	14.8	1.02	1.25	22.6
ONSALE (days from listed to sold)	CONTROL*Ff*:	81.05	72.99	−9.9	58.7	55.7	−5.1	95.02	92.03	−3.2
	TREAT*Ff*:	101.31	150.55	48.6	86.66	83.63	−3.5	92.5	99.17	7.2
	REST OF CITY:	77.3	83.5	8	64.83	66.47	2.5	85.8	92.49	7.8

a correction of the spatial distribution of property values, as a result of filling-in information gaps and asymmetries. This correction is essentially a slight modification of residential location dynamics and of the resulting land value equilibrium. Since the flood-prone properties exhibit a price drop in comparison to the flood-safe properties, it can be suggested that the coastal price gradient in the flood-prone properties became shallower, moving closer to that of the flood-safe properties. This suggests that information policies about anticipated risks can affect the slope of bid-rent functions in a similar manner to realized environmental externalities (see, e.g., Brueckner 2011), whereas previous to the correction the amenity dimension of the coast was overemphasized in relation to its risk dimension. We can thus consider the information shock as a first approximation of actual flood occurrences, and utilize the estimated price discount and sensitivity to occurrence probability to simulate possible reactions of the housing market to future climate, for instance the evolution of risk perception or re-evaluation of most favorable residential areas. Furthermore, since the spatial distribution of housing prices is a key mechanism in various kinds of urban phenomena—from household and firm location equilibria to transportation and land use dynamics—the estimations can be used in urban simulations to assess how hard climate change has to kick in before we start seeing extensive and more general changes in the structure of cities than just housing price shocks.

The findings also suggest that a policy of risk disclosure for real estate markets could be extended to other forms of less obvious risk exposure, such as industrial risks or consequences of exposure to substandard air quality. As suggested above, impacts of climate change-induced changes in sea level or river run-off could be usefully illustrated in flood maps, if the changes are significant enough for markets to be picked up. An additional problem in this respect is that simulated effects of climate change usually represent cumulated effects covering, at least, several decades.

Conclusions

A difference-in-differences strategy was applied to detect possible housing price differentials caused by the public disclosure of high resolution flood maps in Helsinki, Pori and Rovaniemi. The estimations have identified a statistically significant price drop, which, in the case of coastal properties in Helsinki, is sensitive to the frequency or probability of flooding. Additional controls for proximity to water aimed to separate the risk and amenity dimensions of the water body, enabling to assess more realistically the double nature of urban coastal areas. The analysis suggests that disclosure of hitherto not generally available information can be effective in addressing asymmetries and gaps concerning flood risks in the housing market. The analysis provided also indications that the real estate market processes the extra information fairly accurately. The assessment of the drivers of price response and their relative significance, at least for private home owners, does need however additional behavioral study. All in all, risk disclosure may also be relevant as a component of climate adaptation policy aimed at real estate, but in that case the gradual temporal change in the risk level poses additional communication challenges.

We propose to view the flood maps as “informational zoning” that induce a spatially selective short-run shock in the market. Lastly, we suggest that the process should not be studied only as a housing market shock, but utilized in urban economic simulations to assess modifications in the residential location and land value equilibriums under future climate.

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Conflict of Interest The authors declare that they have no conflict of interest.

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IV

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Utilizing the SLEUTH cellular automaton model to explore the influence of flood risk adaptation strategies on Greater Helsinki's urbanization patterns

In revision stage with *Computers, Environment and Urban Systems*.

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Abstract: A cellular automaton model (SLEUTH-3r) has been utilized to explore how long-term urbanization parameters are impacted from alternative flood risk management strategies. The model is implemented in the Greater Helsinki region at a 50 by 50 meters spatial resolution and with a forecast horizon until 2040. The current urbanization trend is driven by edge and road-influenced growth with moderate growth rates. Its main features are the consolidation of existing built-up land and loss of those green spaces that are embedded in the urban tissue, and that the most intense growth of built-up land is expected to happen in flood risk areas. This baseline is compared to strategies that test various responses of the planning system to real estate market forces and the spatial distribution of flood risks. A set of scenarios translates property price effects of flood risk information into various attraction-repulsion areas in and adjacent to the floodplain, while a second set explores varying degrees of restricting new growth in the flood risk zones without reference to the market.

The simulations indicate that growth under all tested scenarios is distributed in a more fragmented manner relative to the baseline, which can be interpreted favorably with reference to house value formation and increased access to ecosystem services, although understanding the indirect effects of reduced growth rates is not easy. Moreover, there are indications that demand for coastal flood-safe properties does not automatically translate to refocusing of development toward those areas, unless planning interventions orchestrate this redistribution; the character of the planning system with respect to market drivers and the spatial distribution of risks and amenities is thus important. A number of methodological aspects are also identifiable. On one hand, incorporating econometric estimates into urban dynamic modelling has been possible and has highlighted the integrative nature of fine resolution urban simulation models in assessing urban adaptation strategies. At the same time, the need to better integrate cellular automata models with urban microeconomic models will resolve many issues in how growth potential is distributed over urban space.

Keywords: urbanization, flood risk management, adaptation strategy, urban growth scenarios

1. Introduction

Urbanization in coastal areas is typically characterized by high concentrations of population, infrastructure, and human activity, following the various social and economic advantages offered by proximity to the sea and coastal ecosystems. But coastal areas also entail risks, notably flooding. A main issue in the link between urbanization and flooding is the fact that the pronounced benefits of coastal areas often obscure the hazards of those areas – the mechanisms behind urban development and investment are often overdriven by amenities while downplaying the risks. As coastal flooding is expected to induce ever-increasing economic losses (e.g. Nicholls and Cazenave 2010; Gerdes 2012; Neumann et al. 2015; for Helsinki, Venäläinen et al. 2009; Parjanne and Huokunna 2012; for the wider Finnish context, Perrels et al. 2010), owing to unsound urban development in relation to current flood risks upon which the impacts owing to changing sea level and hydrological patterns are overlaid, the need for adaptation strategies that take a comprehensive stance toward the functioning of urban areas has become recognized (Ruth and Coehlo 2007; Aerts et al. 2014).

However, adaptation and urbanism are notably large and disconnected arrays of research, whereas evidence-oriented modelling frameworks that bind the pieces together are rare. Research typically focuses on direct effects (cf. Meyer at al. 2013) and specific economic sectors (e.g. the housing market; Daniel et al. 2009), although wider-scoped modelling approaches are gaining momentum (Hallegatte 2008; Perrels et al. 2010; Boesch et al. 2014). The gap may be due to the uncertainty and time horizon involved in the evolution of urban areas, as opposed to more graspable phenomena such as quarterly construction volume or urban development targets. Concerning uncertainty, urbanization is driven by a compound of sociopolitical, cultural, and economic drivers with behaviors that can deviate significantly from what models predict; macroeconomic conditions, the behavior of investors and construction companies, and the response of the planning system to market forces are a few examples. If the uncertainty is too large to move past qualitative narratives toward quantified scenarios, decision makers in adaptation will be reluctant to account for urban dynamics. Concerning time horizon, urban evolution involves gradual changes. It is often overlooked that decision makers seek clear market signals. Markets, however, react to strong immediate changes, whereas urban evolution is considered, if at all, in a rudimentary manner. Moreover, it is also worth noting that municipalities often have to reconcile wishes for strict land use policy with pragmatic development targets (Peltonen et al. 2006; Votsis and Perrels 2016). Still, urban dynamics ought to be policy-relevant as they set the context for adaptation and resilience. Urbanization influences directly or indirectly all the components of the risk of natural hazards as defined by the IPCC (2012), namely, exposure (e.g. heightened intensity of coastal development), vulnerability (e.g. the profile of sectors and population in flood prone areas), and hazard severity (e.g. loss of flood-regulating ecosystems).

This study looks into flood risk management and urban dynamics in the context of Finland and its capital region, the urban area of Helsinki. Finland set up its national climate adaptation strategy (Marttila et al. 2005) in response to the EU Water Directive (European Communities 2000). A follow up to the strategy was reviewing flood risks and releasing high resolution spatially explicit flood risk maps that communicate the geographical extent and floodwater height for various return periods (Dubrovin et al. 2007; Barneveld et al. 2008; Sane et al. 2008). The flood risk maps concerned flooding from river and lake systems and periodic sea surges, which, together with extreme urban downpours, are the main sources of flooding in Finland. In coastal Helsinki, the disclosure of flood risk maps was an effective policy instrument as it corrected market imperfections surrounding non-obvious climate-related risks (Votsis and Perrels 2016). In particular, price/m^2 and demand in properties inside coastal flood-prone areas, as indicated by the maps, were adjusted downwards, while nearby coastal flood-safe properties exhibited price and demand increases. The price discounts depend on flooding probability and further examination showed that the relation between price discount and probability is a bounded-rational (cf. the work of Kahneman and Tversky) translation by home buyers of damage probability into expected damage cost (Votsis and Perrels 2016).

From an urban and regional research viewpoint, and returning to the previously discussed research gap, while the above study quantified how the residential real estate market processed new information so as to better reflect the spatial distribution of coastal risks and amenities, it provided no insights into the wider impacts of the policy instrument on urban development dynamics. These wider links are missing elsewhere, too. Studies that identify impacts and develop strategies tailored to specific Finnish municipalities are available, but despite the politics surrounding sound land use regulation versus how urban development is realized in actuality, the understanding of the links between flood management and urban dynamics has never really took off. For instance, the regional planning authority of Helsinki assessed regional climate change scenarios and impacts, identifying key areas of action (HSY 2012). While the strategy rightly stipulates that future land use plans shall be developed by taking the impacts of climate variation, extreme events, and climate change into account, and recognizes the value of comprehensive land use planning, two opportunities for further refinement are evident. Firstly, the proposed climate-proofing land use measures would benefit from a more thorough understanding of how climate-related impacts are overlaid on the growth *dynamics* of the urban region, as opposed to impacts being related in an ad hoc manner to a *static* vision of the city. Furthermore, understanding the impact of adaptation-relevant behavioral and physical interventions on urban growth dynamics is missing. Secondly, it is evident that studies of urban adaptation to climate-related impacts jump rather quickly to the field of climate change scenarios before clarifying the current relation between flood risk policy and urban growth dynamics.

In responding to the above issues and in extending previous evaluations of climate-related policy instruments, this paper explores the utility of the SLEUTH cellular automaton model for adaptation research, flood risk management, and in linking urban modelling and urban adaptation research. The merit of cellular automata is their capacity to both generate forms consistent with known urban processes and to optimize those forms (Batty 1997) by simulating how different development strategies result in actual patterns of urbanization at a high spatial resolution. The model thus offers an attractive modelling framework for urban adaptation research, because it can explore both the behavior of the adapting system and the potential impacts of adaptation interventions. The aims of this study are twofold. Firstly, to offer a high-resolution implementation of the model while testing the incorporation of relevant econometric information. Secondly, to demonstrate that the type of modelling offered by SLEUTH provides a useful platform to better understand and incorporate urbanization dynamics, especially urban form and growth, in adaptation research.

The study calibrates SLEUTH-3r for reproducing observed urban development patterns in Helsinki's urban region between 2000 and 2012, and is subsequently used to forecast and assess three main scenarios. The first scenario forecasts the evolution of current urbanization trends as identified in the calibration stage. The second scenario (with two variations termed sub-scenarios) simulates a market-led adaptation process that relies on flood risk information and subsequent price and demand adjustments in the residential real estate market. The third scenario (with three variations) simulates a planned adaptation process that relies on regulating the location of future growth without reference to market dynamics. From a spatial policy view (cf. Echenique 2015), the former strategy is as a behavioral regulation of space that relies significantly on information dissemination investments, while the latter strategy is a more straightforward regulation of space akin to traditional zoning.

2. Methodology

2.1. The SLEUTH and SLEUTH-3r models

SLEUTH (**s**lope–**l**and use–**e**xclusion–**u**rban–**t**ransportation–**h**illshade) is a cellular automaton model of urban growth and land use transitions (Clarke at al. 1997; Clarke and Gaydos 1998). This study implements SLEUTH-3r (Jantz et al. 2010), a modification of SLEUTH that maintains its original functionality and theoretical underpinnings, but improves computational performance and introduces additional calibration metrics. Cellular automata (von Neumann 1951, 1966; Batty 1997, 2007) are computational frameworks that model in discrete time bottom-up interactions between elementary spatial entities (cells). They consist of cells in an $n*k$ lattice, initial and possible qualitative states of a cell, and transition rules that function as cellular interaction rules and govern the states of cells. SLEUTH functions with five transition rules: dispersion, breed, spread, road gravity, and slope, which jointly reproduce four distinct types of urban growth: spontaneous, new spreading center, edge, and road-influenced growth (Jantz et al. 2003).

SLEUTH has seen widespread use across the world (Gazulis and Clarke 2006; Chaudhuri and Clarke 2013), including in the urban adaptation context (Aguejdad 2012). Earlier versions have been implemented also in Greater Helsinki by Caglioni et al. (2006) and Iltanen (2008). Its utility stems from its transferability, straightforward implementation and computational efficiency, interpretability, and universalizability (Clarke 2008; Silva and Clarke 2002; Jantz et al. 2003). The limitations of modelling urban growth via non-customizable ad-hoc transition rules rather than implementation of spatial economic theory is a concern (Kim and Batty 2011). However, the model's value in the context of more elaborate urban economic models is its high spatial resolution, standardized and easily accessible input needs (compare to the amount and diversity of data needed by CGE or LUTI models, for instance), and first principles approach that focuses on adapting a transparent set of spatial interaction assumptions into real-world settings. Concerning the last feature, it is noteworthy that SLEUTH abstains from imposing the strong economic assumptions found in equilibrium models, and is therefore able to accommodate a fair diversity of urban policy and urban and regional planning viewpoints.

2.2. Data, pre-processing, and choice of spatial and temporal scales

SLEUTH-3r was calibrated to capture growth dynamics in Helsinki's urban region at a 50x50 meters spatial resolution. The modelled area contains the full extent of the capital region's constituent municipalities and is similar to prior SLEUTH implementations in the region (Caglioni et al. 2006; Iltanen 2008). It should be noted that an urban region's development ultimately depends on regional, national, and international flows, but it is assumed here that the chosen extent captures accurately the region's growth dynamics, since its development has been fairly isolated from bordering regions, which have economies notably too small to affect the spatial dynamics of the modelled extent. The model was calibrated on data that cover the 2000–2012 period, a choice that is supported by literature indicating that SLEUTH performs better when calibrated on short historical timeframes (Candau 2002; Clark and Lincoln 2008). Figure 1 displays the urban growth observed during 2000-2012 for the whole region (left image) and its coastal areas (top and bottom right images). As an illustration, the coastal images display the floodplain's maximum extent, i.e. the zone with a 1:1000 annual flood probability (source: http://www.environment.fi/floodmaps) and a non-overlapping flood-safe zone within 300 m from coast that, added to the floodplain, represents a homogenous real estate market.

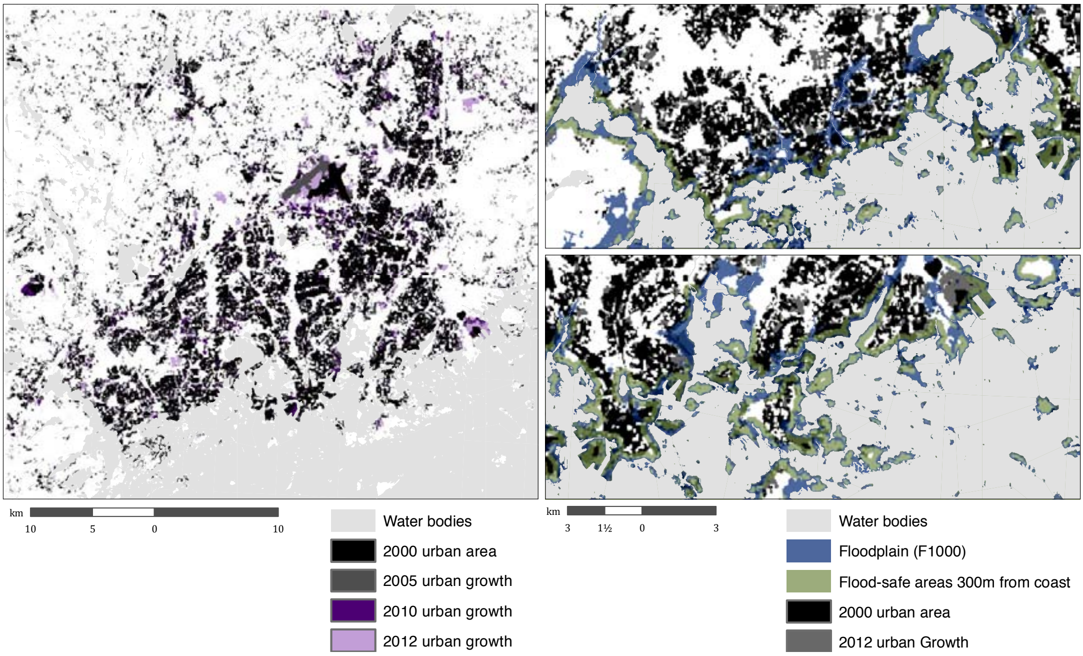

Figure 1: Observed growth in Helsinki between 2000 and 2012

The choice of a somewhat coarser spatial resolution than that of the source data (10 and 20 m) is guided by the aim to reproduce urban development processes at a land unit that represents accurately socioeconomic aspects of those processes. On one hand, the upscaling to 50 m is a reduction in the accuracy of the digital representation of the urban environment. On the other hand, the unit of land at which urban development is reproduced needs to reflect also human-behavioral aspects of land development in the urban area of interest, notably the behavior of real estate markets and the construction sector. If SLEUTH-3r is calibrated at a 10 or 20 m resolution, state transitions of single grid cells imply that development proceeds each time-step at patches of land sized 10x10 or 20x20 m. This is not observed in the study area. New development consists of approximately 50x50 m patches and finer resolutions would imply that urbanization occurs in unrealistically small patches of land. Moreover, the objective for higher spatial accuracy, while justified for the coarse land use data of the past, nowadays entails the danger of moving beyond the scale at which widely accepted processes behind the growth of cities operate (see Fujita 1983; Anas et al. 1998; Brueckner 2011).

Nevertheless, balancing the accuracy of the urban environment's digital representation with the fidelity of the simulated socioeconomic processes includes obvious trade-offs. In the present case, it is assumed that upscaling from 10/20 m to 50 m is a reasonable loss in digital representation accuracy for gaining faithfulness in the market aspects of urban development.

The input layers (Figure 2) are sized at 853x774 pixels (42.65x38.7 kilometers). All of the data sources used in the calibration are registered open governmental or municipal data.

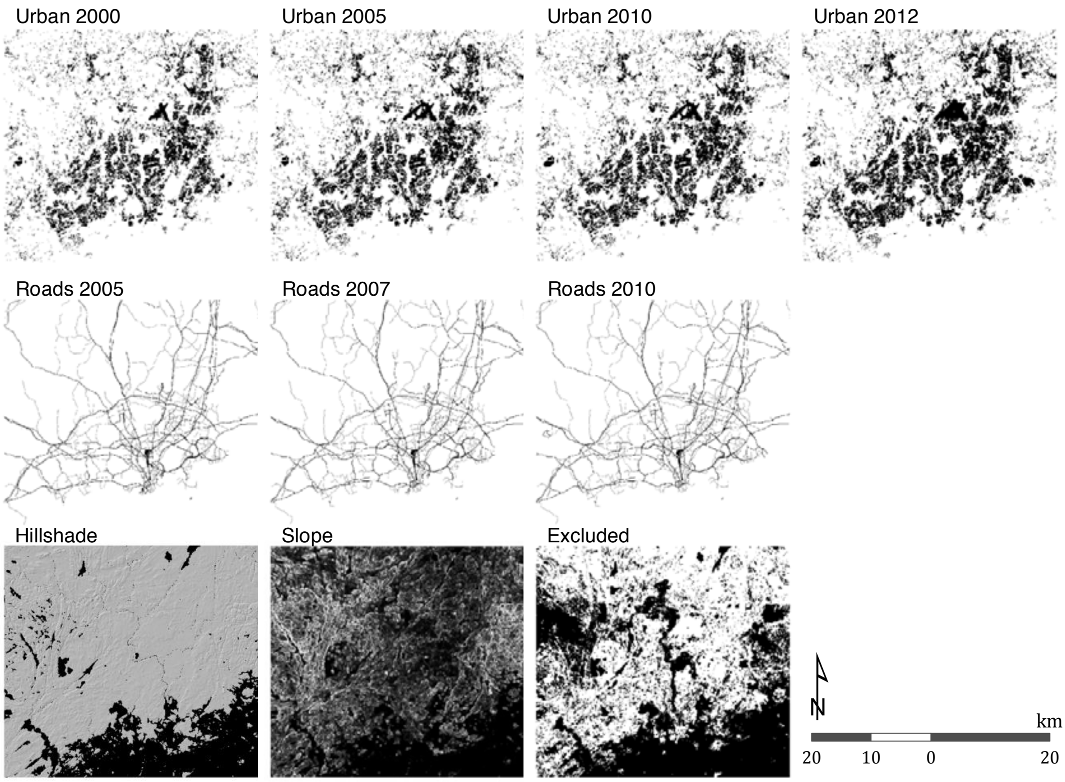

Figure 2: Inputs; top: urban-nonurban, mid: transport network, bottom: topography and growth constraints

The urban layers for the seed year of 2000 and control years of 2005 and 2010 were derived from the Finnish National Land Survey's 10-meter SLICES dataset, which is a multisource raster representation of land use and infrastructure. Control year 2012 was derived from a 20-meter version of the CORINE land use/land cover product provided by the Finnish Environment Institute. The procedure of upscaling the land use data to a 50 m resolution involved the following steps in a GIS software. Firstly, the pixels of the original land use raster files were reclassified to urban and non-urban and subsequently resampled from 10 (years 2000, 2005, 2010) or 20 (year 2012) meters using the nearest neighbor resampling option. Secondly, an empty vector lattice consisting of 50 m grid cells was created to serve as the GIS Masterfile that contains all calibration layers in its attribute table. The vector lattice was created by using the geometry of the resampled 50 m raster files as the guide for its spatial extent and alignment. This ensured that the cells of the vector lattice were exactly aligned with the cells of the re-sampled land use rasters. Thirdly, the pixel values of the four resampled urban/non-urban rasters were transferred to the polygon cells of the vector lattice with a raster to polygon operation. A new attribute was generated for holding the urban/non-urban codes of each year. Gathering all the urban layers in one vector file was preferred, because it greatly assisted and sped-up quality checking and consistency between the four years.

The transport network was derived for years 2005, 2007, and 2010 from the vector version of the National Land Survey's topographic database. This database is a complete representation of natural and man-made features in the Finnish territory at the scale of 1:10000, but excludes a thorough representation of land use/cover (which is provided by the abovementioned SLICES and CORINE raster products). The vector lines of the transport network were filtered to include the intended transport types and transferred to the aforementioned GIS Masterfile with a vector-to-vector selection procedure and by assigning a weighted pixel scheme to reflect different accessibility values. The represented network includes Ia and Ib highways, IIa and IIb mid-size roadways, and the commuter rail and metro lines. A weighted classification schema was employed, with Ia-b, rail, and metro routes given a weighted pixel value of 100 (high accessibility) and IIa-b roads a value of 25 (medium accessibility). In earlier stages of this study, the dense network of local IIIa and IIIb roads was also included with a weighted pixel value of 1 (low accessibility), but was dropped because the chosen spatial resolution misrepresented their influence on development and introduced significant uncertainty in the calibration process. Since the commuter rail lines are included in the transportation layer—as opposed to informing indirectly attraction-repulsion values—they are allowed to influence directly urban development. This choice is in accordance with historical patterns of urban development in the region, which indicate a strong influence of commuter rail lines. Use of commuter rail is furthermore part of the region's urban development strategy, with the majority of the population relying on a comprehensive public transport system, part of which are commuter trains.

The slope and hillshade layers were derived from the Finnish National Land Survey's 10 m digital elevation model (DEM) from 2013. The DEM was first resampled to 50 m by using a bilinear interpolation algorithm, before calculating the hillshade and slope values. Slope was calculated by using the default 'percent rise' algorithm of ESRI ArcGIS, as SLEUTH's formulas were developed to work with this operationalization of slope.

The exclusion layer was assembled by using as sources of land constraints the NATURA 2000 polygons provided by the Finnish Environment Institute, protected areas contained in the aforementioned SLICES dataset, and zoning maps provided by the Regional Council of Uusimaa, which is the planning authority of the broader region containing Helsinki's urban area. The exclusion layer was prepared as an exclusion-attraction surface (Jantz et al. 2010), where values from 0 to 49 denote attraction to development, values from 51 to 100 denote repulsion of development, and the value of 50 signifies a neutral role. In the exclusion layer used in calibration—i.e. for reproducing the observed urban development of Helsinki from 2000 to 2012—areas completely excluded from development were assigned a value of 100. These areas represent natural conservation areas according to EU or Finnish legislation, formally designated urban parks, formally designated sports and recreation areas, water bodies, and 'no building rights' areas according to the regional land use plan. Areas available to development were assigned a neutral value of 50. The exclusion-attraction surfaces that were used to compile and simulate the alternative scenarios are described in section 2.4.

2.3. Scenarios for flood risk management

In response to the need for better understanding the links between flood risk management and urban growth dynamics, three main spatial development scenarios were simulated with the objective to illustrate how the assessment of alternative flood risk management strategies can be incorporated into dynamical urban modelling. The three scenarios are called business as usual, market response, and development restrictions and are explained in the remaining of this section. Future growth under each scenario was forecast by modifying the exclusion-attraction layer that represents each scenario. All simulations have used the set of forecasting growth coefficients identified in the calibration stage (sections 2.2, 2.4, and 3.1).

Business as usual (BAU) scenario: The BAU scenario assumes that historical urban growth patterns, as observed in the period between 2000 and 2012, will continue unaltered until 2040. Future urban growth is forecasted in this scenario by keeping unmodified the exclusion-attraction layer with which the model was calibrated to reproduce observed growth (described in section 2.2).

Market response scenarios (MRa and MRb): The MR scenarios assumed a bottom-up, information-led adjustment process. Urban growth in flood-prone areas is modified by price (MRa) or price and demand (MRb) adjustments in the housing market, induced by publicly disclosed flood risk levels. The specific growth adjustment in each flood-prone area is guided by the sensitivity of price adjustments to flood risk level. The process is grounded on the market adjustments to coastal flood risk information identified by Votsis and Perrels (2016) for Helsinki's coastal region. Their study examined a 300 m buffer zone from Helsinki's coast, which contains all flood risk zones plus flood safe areas. The flood prone and flood safe areas inside this 300 m buffer differ only in whether they are flood risk or flood safe and are otherwise identical in terms of properties, the built and natural environment, and market behaviors. Consequently, the 300 m buffer plus the floodplain provided a market area in which the differential effects of flood information on properties indicated as flood prone versus those indicated as flood safe by the published flood risk maps could be correctly identified. It was assumed that the price-per-square-meter discounts in housing prices that correspond to various flooding frequencies serve as an indicator of a market-led reduction in the attraction of various flood-prone coastal areas to future development. Empirical support for this assumption is provided by Mayer and Somerville (2000), who found that relative changes in property prices lead to a statistically significant change in the growth of the housing stock. The estimations of Mayer and Somerville (2000) were used to translate the spatially variable drop in housing prices identified by Votsis and Perrels (2016) to a drop in the expected housing stock. This relationship was then linearly rescaled to the pixel value range of 51-90 to reflect varying degrees of repulsion to development in SLEUTH's exclusion layer. The increase in price per square meter and notably the indications of increased demand for coastal properties immediately outside the flood zones identified in Votsis and Perrels (2016) was treated in two ways. Scenario MRa treated those areas as neutral to development (value of 50), while scenario MRb assigned a 10% attraction premium relative to the neutral areas. Flood safe areas within 300 m from the coast, which are areas that do not overlap with the flood risk zones, were left as neutral to development in order to enable meaningful interpretation of the impact of flood management practices alone. Lastly, flood prone areas that are indicated as artificially protected in the flood risk maps were assumed as having no change in their attraction-repulsion value. This was based on Ludy and Kondolf (2012) who report no flood risk awareness in home owners of protected flood prone areas. Table 1 summarizes the aforementioned calculations and the resulting, non-overlapping, flood safe and flood prone areas. The naming follows the nomenclature of the official flood risk maps in Finland. Flood risk levels are noted as F*f*, where *f* denotes the return period; for instance, F5 denotes a flood occurring at least once every five years. Return period *f* can be translated into flood event probability 1/*f*; for instance, an F5 event corresponds to a flooding probability of 0.2 or 20% chance. Areas that are marked as F*f* are flood prone areas with a flood risk level that corresponds to *f*.

Table 1: Calculation of exclusion-attraction values for in the market response scenario layers

Flood risk level (F*f*; *f*: return period)	Property price discount [(a)] (%)	Decline of housing stock [(b)] (%)	Pixel value in scenario layer
F5	29.49	2.36	89
F10	30.14	2.41	90
F20	25.49	2.04	81
F50	10.39	.83	51
F100	11.53	.92	53
F250	13.81	1.10	58
F1000	12.11	.97	55
In floodplain, protected [(c)]			50
Within 300 m from coast, flood-safe			50 (MRa); 40 (MRb)
Rest of urban area, no natural protection status			50
Rest of urban area, natural protection status			100

(a) Votsis and Perrels (2016); (b) Mayer and Somerville (2000); (c) Ludy and Kondolf (2012)

<u>Development restriction (DR) scenarios:</u> The DR scenarios assumed a straightforward regulation-led refocusing of urbanization activity. Urban growth in flood-prone areas is modified by top-down zoning restrictions with no reference to market adjustments. Growth is prohibited in F5-F50 areas (DRa), in all flood-prone areas (DRb), or in F5-F10 areas, reflecting different planning tolerances to flood risk threats. Sub-scenario DRa explores the situation where areas with flood frequencies lower than 50 years are neutral to new development, whereas areas with flood frequencies equal to 50 years or higher are completely excluded to new development. In Helsinki's region, this sharp divide at the 50-year mark is evident in the information price discount curves discussed previously as well as in flood damage cost curves (Michelson 2008; Perrels et al. 2010; Votsis and Perrels 2016) and presumably relates to the maximum duration that homeowners expect to own a dwelling: floods with return periods beyond 50 years appear to elicit responses by home buyers (as revealed in realized housing transactions) that are weaker than more frequent floods. DRb explores a more aggressive spatial policy (relative to DRa) in which all flood frequencies are excluded from new development. Conversely, DRc explores a more relaxed spatial policy (relative to DRa) in which only the flood zones of frequencies higher than or equal to 10 years are completely excluded to development, while the areas in other flood frequencies where left neutral to new development.

In all scenarios, existing development is assumed unaffected by the flood-related restrictions and assigned a neutral attraction value. Similarly, the protected natural areas remain completely excluded from development, as defined in the BAU scenario. Table 2 provides a summary of the assessed scenarios and sub-scenario variations, along with the corresponding pixel values in their exclusion-attraction layer.

Table 2: Summary of scenarios and corresponding pixel values in their exclusion-attraction layer

	Scenario storylines
Current trend (BAU)	Recent urban growth patterns continue until 2040. No specific growth policy for flood-prone areas.
Market responses (MRa-b)	Urban growth in flood-prone areas is modified by bottom-up price (MRa) or price and demand (MRb) adjustments in the housing market, induced by publicly disclosed flood risk levels. Growth adjustments in flood-prone areas follow the sensitivity of price adjustments to flood risk levels.
Development restrictions (DRa-c)	Urban growth in flood-prone areas is modified by top-down zoning restrictions with no reference to market behavior. Growth is prohibited either in F5-F50 areas (DRa), in all flood-prone areas (DRb), or in F5-F10 areas (DRc), reflecting different planning tolerances to flood risk threats.

	Pixel value in the exclusion-attraction layer					
	Current trend	Market responses		Development restrictions		
	BAU	MRa	MRb	DRa	DRb	DRc
Flood-prone areas						
Risk level F5	50	89	89	100	100	100
Risk level F10	50	90	90	100	100	100
Risk level F20	50	81	81	100	100	50
Risk level F50	50	51	51	100	100	50
Risk level F100	50	53	53	50	100	50
Risk level F250	50	58	58	50	100	50
Risk level F1000	50	55	55	50	100	50
Flood-safe areas						
300m from coast	50	50	40	50	50	50
Rest of urban area	50	50	50	50	50	50
Rest of urban area; building restriction	100	100	100	100	100	100

2.4. Model calibration

SLEUTH simulates urban dynamics through four types of urban growth: diffusive, new spreading center, edge, and road-influenced growth (Clarke et al. 1997; Clarke and Gaydos 1998; Candau 2002). Diffusive, or spontaneous, growth simulates the appearance of new urban cells unrelated and non-contingent to preexisting infrastructure, while new spreading center growth simulates the likelihood of those spontaneous urban cells expanding. Edge growth simulates the urbanization of nonurban cells that are contingent to existing urban areas, while road influenced growth simulates the spreading of urban areas along major transport corridors. These four types of urban growth are controlled by five growth coefficients that range from 0 to 100: the diffusion, breed, spread, slope resistance, and road gravity coefficients. The diffusion, or dispersion, coefficient controls the frequency that a cell will be randomly selected for possible urbanization due to spontaneous growth. The breed coefficient controls the probability that a cell that became urban due to spontaneous growth will also become a new spreading center. The spread coefficient controls the probability that a new spreading center will generate additional urban areas. The slope resistance coefficient affects all five growth types and controls the extent to which urbanization overcomes areas with steep topography or is contained within relatively flat topographies. The road gravity coefficient controls road influenced growth and relates to the area of influence of transport infrastructure as an urbanization driver. The above descriptions are based on Candau (2002), which contains a fuller exposition. The growth coefficients can be seen as a region's DNA (Gazulis and Clarke 2006), since they encode information about how an initial set of urban cells interacts with manmade and natural features in order to produce a particular urban morphology. Gazulis and Clarke (2006) illustrated how certain combinations of growth coefficients produce known urban morphologies around the world. It should be clarified that a calibrated model is not a scenario in itself, but can produce one that represents the future trajectory of current trends, if the calibration parameters are used unmodified to forecast future growth.

The objective of the calibration process is to identify the combination of values for SLEUTH's five growth coefficients that can best reproduce observed urbanization patterns, as represented in the urban/non-urban input data, for the control years in the selected spatiotemporal scale. The procedure is performed in a brute force manner (Clarke et al. 1997) in three successive stages ('coarse', 'fine', and 'final'), in which the solution space for the coefficients is progressively narrowed down. Originally, the first two stages would use coarser resolutions of the data, but current computational capacity allows the use of the full resolution images across the calibration process. Calibration is guided by evaluating several fit statistics that compare simulated growth to observed growth for a given coefficient set. Dietzel and Clarke (2007) recommend the use of the optimal SLEUTH metric (OSM – the numerical product of seven fit metrics) as a robust replacement of the various ad-hoc approaches used in the past to select the best coefficient sets. Jantz et al. (2010) note that a composite of single fit metrics of various growth dimensions is challenging to interpret. In the context of SLEUTH-3r, they introduced the use of the population fractional difference (PFD) and clusters fractional difference (CFD) as performance indicators of the simulated volume and spatial form of growth, respectively. The metrics range from –1 to 1, with values of zero indicating perfect fit, positive values overestimation, and negative values underestimation of growth.

In this study, model calibration was performed by using the metrics developed specifically for SLEUTH-3r (Jantz et al. 2010). The process employed variables |CFD|, |PFD|, their arithmetic mean, and the average spreads of |CFD| and |PFD| between control years. In each calibration stage, a subset was identified that contained Monte Carlo runs within –/+5% of perfect fit according to CFD and PFD and with no more than –/+10% spread in CFD and PFD across control years. Within that subset, the top-performing Monte Carlo runs were singled out by sorting by the arithmetic mean of |CFD| and |PFD| and identifying the run where the arithmetic mean experiences a sharp rise in relation to the means of the previous (better) runs. It is assumed that this "first sharp rise" of the mean is an indication that performance of the subsequent runs decreases rapidly. The precise rules followed for constructing the search space in each calibration stage were taken from Candau (2002, pp. 54-55). The calibration process otherwise followed the model's official documentation (http://www.ncgia.ucsb.edu/projects/gig/index.html).

3. Calibration results and validation

The calibration produced a model in which simulated and observed data in the control years do not deviate more than |2.1%| in the number of clusters (indicator of the ability to simulate urban form) and more than |4.3%| in the population of built-up cells (indicator of the ability to simulate total volume of built-up land). The mean of the two indicators is |3.2%|. These values are inside the |5%| error range reported by Jantz et al. (2010). The average spread of these accuracies across the control years is less than |2.4%| for clusters and less than |9.8%| for population. The produced set of forecasting growth coefficients is {1, 29, 56, 42, 61}. Tables 3 and 4 validate the calibration of SLEUTH-3r for reproducing accurately observed growth in Helsinki during the control years. Table 3 provides an overview of the calibration stages; the provided metrics measure the ability of each calibration stage's growth coefficients to reproduce the amount (PDF) and shape (CFD) of growth that is observed in the historical data (control years of 2005, 2010, and 2012). Table 4 provides an extended selection of metrics that evaluate the ability of the final set of growth coefficients to reproduce historically observed growth for the three control years.

Referring to the growth coefficients (therefore from a technical point of view), the results suggest that new growth in Helsinki's urban region occurs mainly as continuous expansion of the existing urban clusters, by pushing the urban-nonurban edge forward and by filling-in available land between built-up neighborhoods. A strong attraction of new growth to the transport network is also evident. Diffusive (spontaneous) growth that is unrelated to existing urban clusters or the transport network is rather limited. Topographical variation has also a limited influence on restricting growth, which is in line with the knowledge that maximum allowable slope is not heavily, if not at all, regulated in this relatively flat city. The results have common elements with previous calibrations of Helsinki. Caglioni et al. (2006) report similar coefficients for road gravity (62) and diffusion (2). The setup of Iltanen (2008: 42-43) most closely resembling this study's setup reports similar breed (20) and slope (58) values. Both studies report spread coefficient values that are significantly lower (10-11) than in this calibration. However, more elaborate conclusions cannot be made, since the spatial resolution, historical timeframe, inputs, and overall setup of those studies is different from the present one.

Table 3: Calibration to observed data with CFD and PFD metrics

	Calibration stage			
Growth coefficient	Coarse	Fine	Final	Forecasting
Diffusion	0–24; 6	1–5; 1	1	1
Breed	0–24; 6	20–28; 2	26	29
Spread	40–60; 5	46–54; 2	50	56
Slope resistance	76–100; 6	90–98; 2	94	42
Road gravity	50–100; 10	52–68; 4	56	61
Fit metric				
|CFD| (|spread|) of top run	.0223 (.0308)	.0218 (.0318)	.0209 (.0241)	n/a
|PFD| (|spread|) of top run	.0433 (.0882)	.0430 (.0983)	.0431 (.0981)	n/a
mean(|CFD|, |PFD|) of top run	.0327	.0324	.032	n/a

Table 4: Performance of the final coefficient set for the control years

	Edges	Clusters	Population	Mean cluster size	Mean center	Radius	Avg. slope
Observed value							
2000	59286	5891	97776	16	447, 391	176	4.54
2005	65470	6098	114353	18	447, 384	191	4.48
2010	65734	5655	119930	21	447, 384	195	4.43
2012	67707	5149	143630	27	450, 376	214	4.41
Simulated value							
2005	64054 (–1416)	6033 (–65)	114535 (182)	18 (0)	446, 384 (0, 1)	191 (0)	4.40 (.08)
2010	67037 (1303)	5670 (15)	133000 (13070)	23 (2)	445, 376 (1, 8)	206 (–10)	4.32 (.11)
2012	67845 (138)	5454 (305)	140797 (–2833)	25 (–2)	445, 373 (5, 3)	212 (2)	4.31 (.10)

Differences from observed in parenthesis (negative values: underestimation; positive values: overestimation)

In addition to the best fit metrics provided above, the images of the forecasting calibration stage were compared to the images of actual growth. Table 5 provides the results of the accuracy assessment and the metrics indicate a satisfactory performance of the calibrated model in reproducing observed growth (cf. Chaudhuri and Clarke 2014). The maps of Figure 3 display the differences between simulated and observed growth in the three control years (2005, 2010, and 2012).

Table 5: Accuracy assessment for control years 2005, 2010, and 2012

Year	Overall accuracy (%)	Kappa coefficient
2005	95.92	.86
2010	93.77	.80
2012	92.19	.77

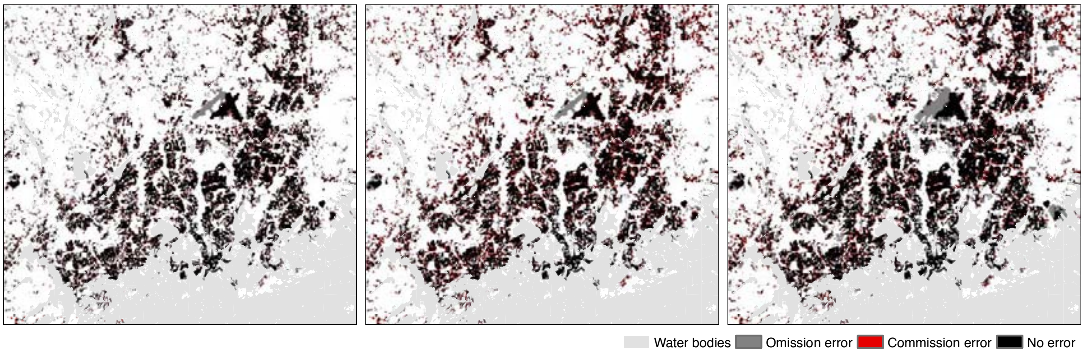

Figure 3: Differences between simulated and observed growth in control years 2005, 2010, and 2012

4. Scenario forecasts

This section presents and discusses the urbanization trajectories predicted for each scenario. For the benefit of clarity, each main scenario with its variations is discussed in its own subsection. The discussion of each scenario focuses firstly on the aggregate characteristics of the trajectories for the whole urban region, followed by the local, spatially disaggregate, characteristics of the predicted trajectories in the coastal and near-coastal flood-prone and flood-safe areas.

4.1. BAU scenario

The current trends scenario, named business-as-usual (BAU), is summarized in Figure 4. The simulation of this scenario is based on the last available data layers (cf. Figure 2 and section 2.2) and indicates the future trajectory of current urbanization patterns, if land constraints and the transport network remain unchanged and no serious exogenous shocks happen in population, economic structure, and the way economic growth is currently distributed throughout Helsinki. This scenario also assumes that development behavior inside the floodplain continues in the future without planning interventions specific to flood risks. This is an important assumption as the market response and development restriction scenarios simulate changes in development patterns when planning interventions specific to food risks are applied.

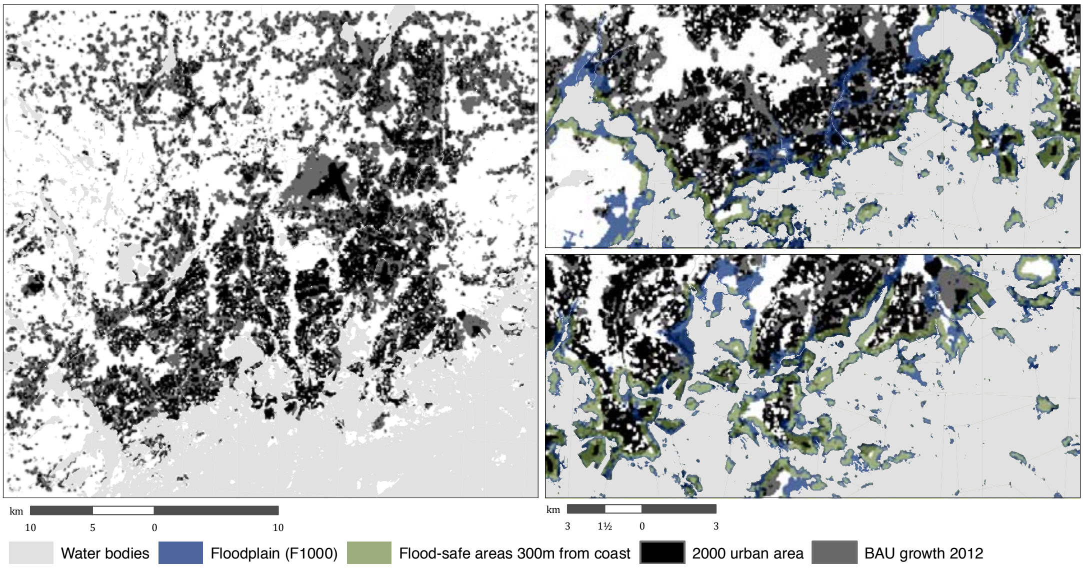

Figure 4: Simulated output image for the BAU scenario in 2040

Figure 5 summarizes nine growth parameters of the BAU scenario. The growth rate of built-up land is overly stable at approximately 2.7% until 2020 and steadily drops each subsequent year reaching approximately 1.3% by 2040. The growth rate trajectory corresponds to almost a doubling of built-up land ('pop'), approximately from 39000 to 66000 hectares. At the same time, the length of the urban/non-urban frontier ('edges') does not appear to change significantly; it increases rather weakly until 2030 and declines subtly afterwards. The growth of the total volume of built-up land while maintaining the length of the urban/non-urban boundary implies that, in addition to a significant decrease of natural land, progressively fewer urban areas will maintain direct access to natural areas. More precisely, the number of built-up clusters ('clusters') will steadily decrease, while the size of those clusters ('cluster size') will concurrently increase, indicating that Helsinki's built-up morphology will become more consolidated and less fragmented. This particular growth behavior links to typical development practices in Helsinki, which have historically used ample space, with preference on sprawling low-density residential areas and a notable absence of a comprehensive preservation plan for green infrastructure. However, developable land is eventually becoming less and the saturation of built-up areas implies that the overall loss of large masses of natural land, which are found mainly at the urban periphery, is coupled with the progressive loss of small green spaces located between built-up clusters across the entire city.

Edge growth is orders of magnitude larger than the other growth types handled by SLEUTH. In light of the aforementioned growth behavior, this indicates for Helsinki that the spreading out from existing built-up areas, with limited leap-frogging, translates to the filling-in of natural areas between neighborhoods. On the other hand, the emergence of areas from spontaneous and new spreading center growth is nearly absent throughout the forecast timeframe. Road-influenced growth is active throughout the forecast timeframe, but declines steadily. This is reasonable, as no new major transport links are simulated in any of the scenarios and therefore any road-influence growth is gradually saturated around existing high access links.

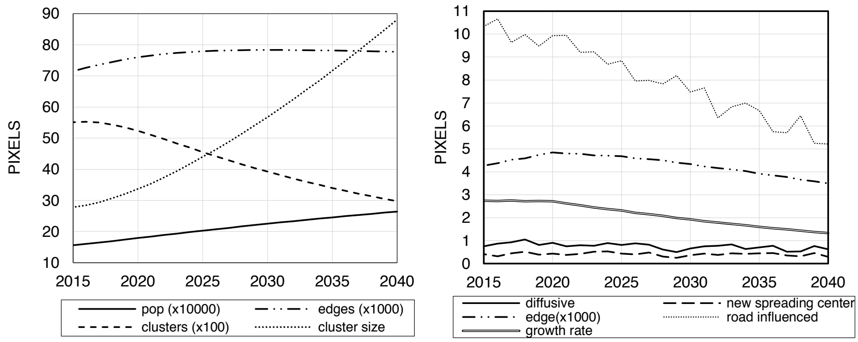

Figure 5: BAU scenario; overall volume and form (left) and growth types (right). One pixel corresponds to an area of 50x50 meters (1/4 hectare).

For Helsinki's residential areas, the majority of unbuilt land is green infrastructure. Its loss represents a multifaceted increase in disaster risk, as the ecosystem services provided by green infrastructure are central in regulating flooding (De Groot et al. 2002; Davies et al. 2011). At the same time, in addition to the loss of natural flood regulation, the consolidation of impermeable areas, assuming that water-absorbing construction materials are not widely implemented, means exacerbation of flood events or their impacts. This is relevant not only for coastal flooding, as the damages of storm-related flooding have been increasing (cf. the urban flood in Copenhagen on 2.7.2011 with € 800 million of damage; see Gerdes 2012). From an aggregate perspective, it can be therefore suggested that, for Helsinki, the BAU scenario represents an increase in both vulnerability (loss of regulating ecosystem services) and exposure to flood-related hazards (increase and consolidation of urban areas). It is worth noting that the loss of green infrastructure increases vulnerability of the housing market to flooding via an additional route. The loss of economic value associated to the loss of proximity to natural areas is widely reported in hedonic valuation literature (Tyrväinen 1997; Tyrväinen and Miettinen 2000; Brander and Koetse 2011; Perino et al. 2014; Siriwardena et al. 2016). This implies an increase in the economic vulnerability of households concurrently with an increase in the abovementioned physical vulnerability and exposure to flood impacts.

The abovementioned aggregate characteristics of the BAU scenario can be complemented by a closer examination of the scenario's local characteristics. In addition to the seven flood risk zones (F5-F1000) of the urban region's coastal areas, and as the morphology of these zones is fragmented, additional flood-safe areas within a certain distance from the coast were explored. These flood-safe areas were categorized into three indicative zones: 0.3, 0.3-1, and 1-10 km from the coastline. The distance of 0.3 km is grounded in the significant homogeneity of highly expensive coastal properties within this buffer, in terms of market behavior and physical characteristics. Beyond 0.3 km and until 1 km from the coast, one observes a second zone of coastal properties that is still of significant value, but does not belong to the far-right end of the price range. Properties between 1 and 10 km from the coast are assumed as representatives of the inland housing market.

The local characteristics of the BAU scenario were identified by applying a 90% threshold to the scenario's cumulative urbanization probability map of year 2040 (end of forecast period). The threshold of 90% (10% uncertainty) is borrowed from common practice in statistical analysis. Since the predicted urban pixels are expressed in probability of cumulative urbanization by a given year, it is assumed that 10% is the maximum allowed uncertainty for the model's predictions of urbanization. The total amounts of predicted built-up cells where counted for the flood risk (F5-F1000) and flood-safe zones (0.3, 0.3-1, and 1-10 km from the coastline). It is important to note that counting the growth in these zones as separate from each other represents an assumption behind flood risk mapping and economic analysis. Even though, for instance, an F1000 flood risk zone may well overlap with an F5 flood safe zone, the flood maps represent these cases as independent (i.e. separate inundation maps for different return periods) which, when overlaid, can represent conflicting information to the public, whereas urban economic analysis also assumes that the demand and price responses of the housing market to these flood risk maps is the compound result of their independent characteristics. Clearly, this assumption merits attention in future research, sorting out truly safe areas independently from return period. However, a question following the identification of non-overlapping safe areas would be, what the reaction of the market is (upon which future development depends, among other things) to areas that are flood safe in some return periods but unsafe in other return periods. A further question would be the relation between binary classifications sound for engineering analysis versus fuzzy, overlapping classifications with which the public and markets operate. In light of the above, this study's counting of urban growth in all the different flood safe and flood prone areas adopted the compound effect assumption for the BAU scenario in order to make the BAU trends comparable to those of the DR and MR scenarios, which certainly contain compound market effects.

Table 5 summarizes the BAU trajectory in the aforementioned flood-prone and flood-safe zones.

Table 5: Local characteristics of the BAU scenario for year 2040 for near-coast areas (90% certainty threshold)

	Built-up land in 2040		**% change from 2012**
Zone	*pixels*	*hectares*	
F5	4636	1159	66.0
F10	422	106	47.6
F20	429	107	44.0
F50	584	146	46.0
F100	1640	410	69.6
F250	635	159	30.4
F1000	1175	294	41.4
Flood-safe (0.3 km from coast)	8226	2057	18.6
Flood-safe (0.3-1 km from coast)	96415	24104	39.9
Flood-safe (1-10 km from coast)	16211	4053	24.0

Of interest are the divergent amounts of growth in built-up land in the various zones. The flood risk areas are set for notably higher growth in built-up land (30-70% relative to 2012) than the waterfront flood safe areas (19% within 0.3 km from coast) and inland (24% within 1-10 km from coast) areas. The transition zone between coast and inland (0.3-1 km from coast) is the exception, with 40% of growth relative to 2012. The high growth rates in the coastal flood prone areas can be related to prior research in the topic (e.g. Bin et al. 2008a; Daniel et al. 2009) that indicates that coastal amenities overdrive decisions in the real estate sector irrespective of the risks that may be involved. In this case, the BAU simulation confirms that the forces driving new urban development overestimate the amenity dimensions while not reacting in par with the flood risk levels. The high intensity of urban growth in risky areas relative to elsewhere in the city poses challenges for the resilience of Helsinki to current flood risks as well as its adaptation strategy to future costal risks. As an illustration, it indicates that a significant portion of the regional economy's resources is channeled toward growth in risky coastal areas instead of safer areas or instead of being invested into flood insurance or flood protection options. It also indicates an increase in the society's exposure and vulnerability to flood risks, as large volumes of urban development typically translate to large volumes of residential building stock, associated public infrastructure, and population.

4.2. Market response scenarios

Figure 6 displays an overview of the simulated output of the market adaptation scenarios, MRa and MRb, in the coastal zone. As introduced in Section 1, these scenarios aim to translate the housing market effects of the public disclosure of flood risk information into gradual urban development effects, so as to better assess its nature as an adaptation policy instrument. Section 2.3 outlined how the sensitivity of price adjustments to different flood probabilities was translated into different pixel values in the exclusion-attraction layer. The difference between MRa and MRb is that the former assumes no price and demand increases in flood-safe areas with 300 m from the coast, whereas the latter assumes a 10% attraction premium in those relative to all other flood-safe areas. These scenarios assume that the planning system adjusts to market forces, rather than constraining them.

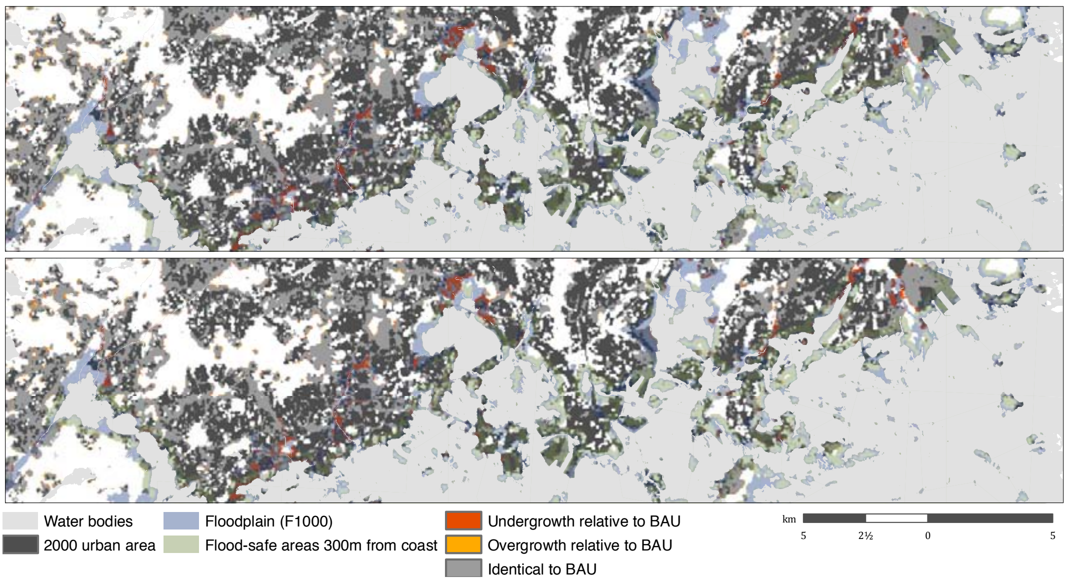

Figure 6: Urbanization under scenarios MRa (left) and MRb (right) by 2040

Concerning the entire region, the simulations show that the information effect translates into a reduction in produced built-up areas relative to the baseline trend by approximately 0.8% (MRa) and 0.7% (MRb) (Figure 7 left). The growth rate is initially subdued by about 0.06% in both scenarios, but it gradually recovers and reaches the baseline rate within approximately 20 years: the growth rate of MRb stops deviating from the baseline in 2033 and MRa follows in 2034 (Figure 7 center). While, in principle subdued growth rates in risky areas are beneficial (see further discussion in Section 5), a discussion of the implications of reduced growth rates should be limited by using only SLEUTH. The deviation from baseline growth rates is rather limited and the indirect economic effects of slightly reduced building production (implied by reduced urbanization rates) are most likely moderate, provided that the fluctuations of the deviations are moderate and the period of instability is not too long. However, Helsinki has a deficit in the provision of residential and work space in comparison to the population inflows. Thus, if reduced growth rates are applied in a city with unmet demand for housing and work spaces, square-meter prices of floorspace may react strongly at some point during the beginning of the forecast. Such a price increase may have more significant consequences.[1]

Morphologically, scenario MRa yields approximately 2% more urban clusters that are about 3% smaller in size relative to the BAU scenario, while MRb yields approximately 1.6% more urban clusters that are approximately 2% smaller (Figure 8). This indicates that the tested policy instrument produces a more fragmented urban morphology and has implications in relation to the BAU, which are discussed in Section 5. Concurrently to fragmentation, the scenario impacts the amount of urban-nonurban edges and the emergence of edge growth, which is the main spatial realization of growth in the baseline scenario. Initially, the amount of produced urban-nonurban edges undergoes a period of negative shock relative to the baseline until about 2028, followed by a re-bouncing with higher amount of edge growth in the remaining years till 2040 (Figure 7 right).

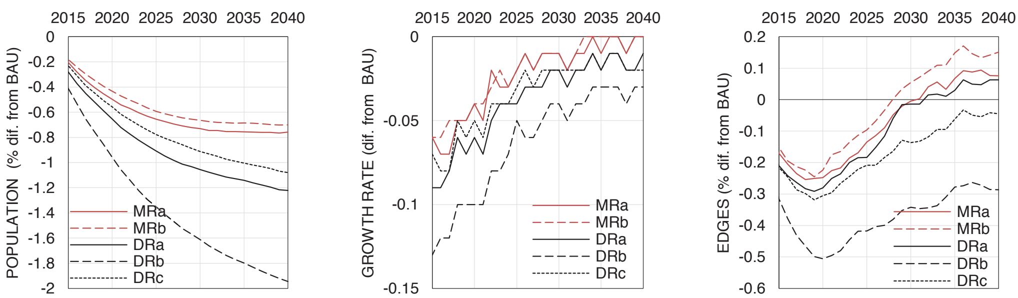

Figure 7: Deviations from BAU in the amount (left) and growth rate (center) of built-up land production, and in the amount of produced urban-nonurban edges (right)

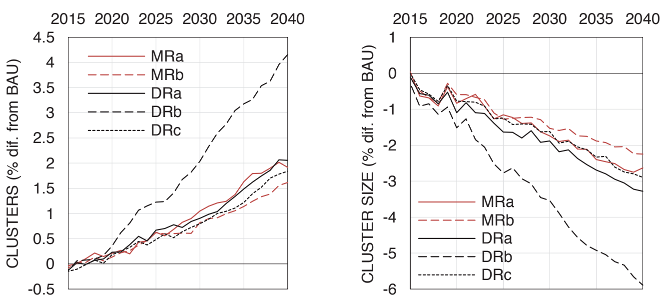

Figure 8: Deviations from BAU in the amount (left) and average size of urban clusters (right)

As with the BAU scenario, the local effects of the market response scenarios relative to the baseline projections are discussed with reference to measuring forecasted growth in different flood-prone and

[1] I acknowledge the contribution to this paragraph of Adriaan Perrels at the Finnish Meteorological Institute.

flood-safe zones (see Figure 9). In the floodplain, most of the differences from BAU appear to follow the pre-set differences in the exclusion-attraction layer. In this respect, the model performs as expected, since it provides output robust to small variations in urbanization constraints. However, there is a subtle indication of non-straightforward spatial spillovers of the constraints in some of the cases. Although scenarios MRa-b impose the same restrictions in all flood risk zones (identical exclusion-attraction values), their end impact on urbanization inside the flood risk zones differs, presumably because the two scenarios imposed different restrictions in the contingent flood safe zone of 300 m from the coast; MRb assumed an increase in demand for coastal but flood-safe properties. The reasons for this interaction may be due to the fact that SLEUTH is able to capture how urban growth in a certain zone is impacted by restrictions in the surrounding areas, which will then require to look more carefully in the way the growth behaviors of neighboring pixels are allowed to interact during growth cycles before making policy-relevant assertions. Moreover, scenario MRb, which only slightly elevated the demand of coastal flood-safe areas relative to MRb, stands out as the only scenario with a clearly positive deviation of 1.7% in the production of built-up land relative to the baseline, whereas growth in these coastal flood-safe areas under MRb is surprisingly negative at – 0.5% relative to the baseline. Beyond the above elements, growth in inland flood safe areas (between 0.3 and 10 km from the coast) under scenarios MRa and MRb is affected in a similar manner.

Since SLEUTH's output growth assumes that urban dynamics are modelled with all market drivers as given except extra planning modifications via the exclusion-attraction layer, and in the case that the above spillover is not a misleading feature of the model (the causal interpretation of spatial interaction in economics is not without challenges; see Gibbons and Overman 2012), the following suggestion can be made. If an increased demand for coastal flood-safe areas is also accommodated by the planning system (scenario MRb, i.e. allowing to reflect demand in the exclusion-attraction layer; see Table 2), then this appears to yield the re-distribution of urban development in the floodplain that is different than in the case where the planning system does not encourage demand for coastal flood-safe properties (scenario MRa). Moreover, the differences between growth under MRa and MRb indicate that if the planning system does not actively respond to demand changes in the real estate market followed by disclosure of flood risks, actual redistribution of development in those coastal flood-safe areas does not appear to materialize.

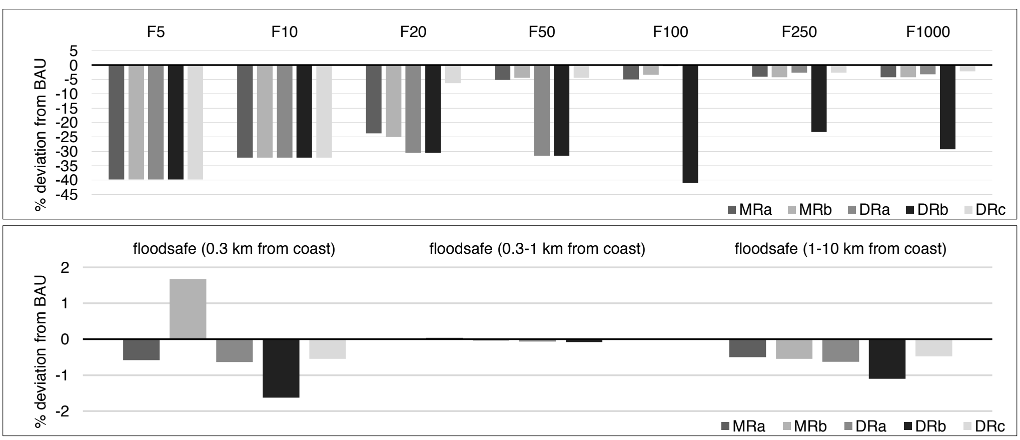

Figure 9: Deviations from BAU in built-up land in 2040 in flood-prone (top) and flood-safe areas (bottom)

4.3. Development restriction scenarios

Further insights into the relation of the planning system to market adaptation mechanisms can be gained by the development restriction scenarios, the main character of which is that the growth restrictions are applied with no reference to the responses of the real estate market to different flood probabilities. They therefore simulate the regulatory restriction of new growth in flood prone areas, regardless of the nuances of how the real estate market responds to information about different flood probabilities. It is thus assumed that the planning system constrains, rather than adjusts to market behavior. Figures 7-9 overview the growth indicators for scenarios DRa-c, while Figure 10 provides an overview of growth in the coastal area under scenario DRb, which is the most illustrative development restriction scenario as it deviates the most from the MR scenarios. The character of scenario DRb is interesting also in the sense that, although flat-out zoning restrictions in the entire floodplain are unlikely, they can realize as a de facto situation if sea level rise renders the floodplain undevelopable. This topic is beyond this study's reach and it obviously contains an untested assumption that sea level rise happens at once and its extent coincides with the floodplain.

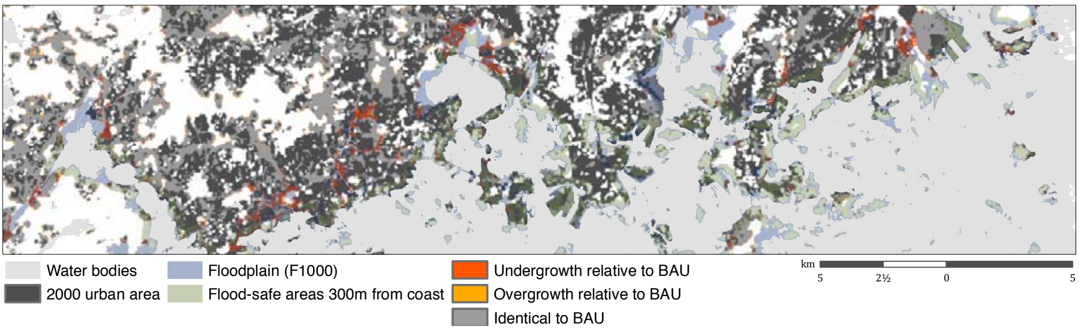

Figure 10: Simulated output images for scenarios DRa (left), DRb (center), and DRc (right) in 2040

The production of total amount of built-up land (Figure 7 left) and annual growth rate (Figure 7 center) are impacted the most by the aggressive development restriction scenario (DRb), while the relaxed (DRc) and middle-way (DRa) scenarios keep fairly near market adaptation scenarios MRa-b. In particular, DRb yields 1% less amount of built-up areas relative to the baseline by 2020 and 2% less amount by 2040. By contrast DRa and DRc produce approximately 0.6 and 1.1% less urban land relative to the baseline by 2020 and 2040, respectively. In terms of growth rate, DRb subdues the baseline rate by 0.1% in 2020 and 0.03% in 2040. The impact of DRa and DRc stays fairly close to MRa-b and all DR scenarios minimize their deviation from the baseline by 2040. It is worth noting that none of the DR scenarios recovers to the baseline growth rate by 2040, as opposed to the market adaptation scenarios that recover by 2034.

Morphologically (Figure 8) the DR and MR scenarios agree in that they all produce more fragmented urban growth relative to the baseline. Scenario DRb stands out from the rest by producing by far the most fragmented urban morphology, with 4% higher amount of built-up clusters that have 6% smaller size relative to the baseline by 2040. In contrast, the morphological impacts of DRa and DRc are entangled for the most part with those of the MR scenarios; DRa produces 2.1% more urban clusters that are 2.9% smaller than the baseline by 2040, while the respective quantities for DRc are 1.8% and 3.2%. Concerning the amount of urban-nonurban frontline (Figure 7 right), DRa trails just below scenarios MRa-b; it takes an initial hit by producing in 2020 0.3% less amount of urban-nonurban edges relative to the baseline and re-bounces to positive after about 2030 with about 0.1% more edges.

Concerning local effects (Figure 9), a noteworthy feature of the DR simulations is that a flat-out exclusion policy for the entire floodplain, as represented by scenario DRb, yields a –1.6% deviation from the baseline in the production of built-up land in the coastal flood-safe zone (300 m from the coast), while the rest of the scenarios have similar deviations to scenario MRa of about –0.5% relative to the baseline. The underlying exclusion-attraction values in this flood-safe area are the same for all scenarios (neutral value of 50) except MRb. Compared to scenario MRb, which actively redistributed development in the same area, this ties in with what was indicated previously that—given a modelling approach that assumes that market forces are inherent in the end result of simulations—demand for flood-safe locations will not automatically translate to refocusing of development. The additional suggestion here is that a planning system that is entirely insensitive to different flooding probabilities will induce disproportional changes in areas that are communicated as safe from risks.

Lastly, all scenarios have near-zero deviation from BAU in the flood-safe areas between 0.3 and 1 km from the coast, and the differences reappear in the flood-safe areas between 1 and 10 km; these two zones have identical land constraints in all scenarios, whereas in inland flood-safe areas between 1 and 10 km from the coast, the effects of the various reappear. Although interesting, this feature cannot be explored with the current model setup. While potentially connected to the spatial interaction effect of growth constraints in the exclusion-attraction layer that was discussed earlier, a closer look than afforded by this study is needed mainly on the way SLEUTH models how growth potential in the entire modeled area is affected by imposed restrictions in particular areas.

5. Policy discussion and conclusions

A major theme that appears through the tested scenarios is that constraining urban development in flood risk areas produces urban morphologies that are more fragmented relative to the baseline—indicated by an increase of the amount of urban clusters and concurrent reduction of their size—irrespective of whether the interventions stem from a planning system that adjusts to market forces (MR scenarios) or constrains those forces (DR scenarios). This implies that green spaces are more fragmented as well, with a larger proportion of total built-up land exposed or proximate to ecosystem services. So, it can be maintained that planning interventions that restrict growth patterns in flood risk areas will slow down the consolidation of urban areas characterizing the BAU scenario, which combined with reduced growth rates may encourage the preservation and spatially heterogeneous presence of flood-regulating and other ecosystem services. As discussed in Section 4.1, alleviating the loss of ground-based ecosystem services that are embedded in the urban tissue reduces the loss of significant amounts of wealth in the real estate market (thus reducing vulnerability), while increasing the exposure of coastal residential areas to ecosystem services embedded in the urban tissue.

While the scenario simulations indicate a halt in varying indicators of growth, only the main driver of growth as modelled by SLEUTH (in this case, edge growth – see Section 2.4) is affected. The other types of urban growth simulated by SLEUTH are not affected by the scenarios (diffusive, road-influenced, and new spreading center growth). This implies that constraining growth in risk areas without changing the transport infrastructure is able to change the morphological parameters of these areas, but does not change the underlying urban growth drivers as modelled by SLEUTH. The halting of growth rates inside risky areas in combination with the morphological benefits can be at first assumed, as in the previous paragraph, as beneficial for the coastal zone, but as discussed in section 4.2 this is not the entire story and indirect effects must also be accounted for. Although the simulated changes in growth rates are rather weak, it is important to understand how the impacts of these deviations from the baseline are distributed across urban economic sectors.

An interesting comparison between policy instruments that constrain market forces versus ones that respond to those forces has also been argued in Sections 4.2 and 4.3. The simulations indicate that different land constraints can have a differential redistribution of development activity in and near the area of application, and that demand for amenity-rich but safe locations will not always translate to actual refocusing of development. In this respect, the spatial character of interventions becomes important, as interventions that track and respond to market adjustments caused by increasingly transparent climate-related risks appear to be a necessary element in refocusing urban development. The tolerance of the planning system to the levels of flood risk and to market behavior is therefore a parameter in the way wealth and investment in the form of capital stock and infrastructure are distributed in relation to climate-sensitive risks and amenities so as to better reflect the spatial configuration of risks. Based on the results, however, it is unclear whether a planning intervention fully following market responses is preferable over one that poses ad hoc but gentle restrictions according to flood risks. In any case, the simulations can be taken as an indication that a combination of market-led/information-based and zoning-based regulatory elements can provide the necessary precision and agility for a flood-related adaptation strategy.

It is also noteworthy that a policy that excludes the entire floodplain from future development translates to reductions between 25 and 40% in the produced built-up land relative to the baseline. On one hand, as discussed in Section 4.1, these elasticities are indicative of the volume of development that would occur in the floodplain without any intervention. On the other hand, when looking at the scenario performances inside the various flood risk zones, it is chiefly the fully restrictive scenario that confirms the fact that a full exclusion of the flood plain from future development irrespective of market forces is capable of subduing a tremendous amount of growth, whereas all other scenarios that take less restrictive approaches appear to induce results quite near to each other, irrespective of the method used to quantify the development restrictions. This may strengthen the view expressed previously, that development restrictions that are spatially flexible, rather than monolithic throughout the floodplain, may be able to re-distribute growth more elegantly without inducing a shock with magnitudes that intuitively appear too problematic for urban development. It also begs the question of where the subdued growth is rechanneled to, which brings us to a rather complex issue. Additional tests need to be performed in order to understand how SLEUTH handles development potential that is realized in a baseline scenario with certain land constraints, but is unrealized in scenarios that impose additional (to the baseline) land constraints. It would be particularly interesting to see whether alternative land use change models would spatially redistribute growth in an altogether different manner than what is presented in this analysis. The problem is in fact a difficult one, and it further relates to the ability of models informed by complexity theory to calculate the development potential of an urban area before and independently of the spatial interaction algorithms used distributing this growth. This, unfortunately is not currently addressed by cellular automata models. The standard approach in urban and regional research is to look into microeconomic theory, which explains how total regional and national economic output is distributed over an urban area through new investments and growth in capital stock and infrastructure, based on the location decisions of firms and households. This is beyond the scope of this analysis, but future research would certainly need to better relate cellular automata models to the way urban microeconomic theory explains why cities exist and how they evolve as they do.

Regardless of the uncertainties that are common in any empirical approach, translating econometric estimations to scenario input has been a straightforward task, and the defining parameter in this task is the particular way the statistical estimations are translated to pixel values. This paper offered one possible translation, but there are undeniably other approaches. The modelling and forecasting capacity with respect to spatially disaggregate dynamics is SLEUTH's main strength, because this kind of information is typically left unaccounted for in most adaptation studies, resulting in partial adaptation knowledge that is missing essential spatial parameters. Such output is of ever-increasing importance; as the need for more context-aware strategies rises, SLEUTH can contribute on one hand to vulnerability and exposure assessments, and on the other hand to physics/engineering-based hazard research.

In closing, it is important to note that SLEUTH's distinguishing feature in helping to navigate through alternative urban futures is its ability to simulate the distribution of urban growth at a fine geographical grid. This benefit will be boosted if coupled to a model that assesses monetary costs and benefits, which at first means understanding the impact of SLEUTH's forecasts to indicators external to the model. For instance, if growth is constrained or promoted in a part of the city, and SLEUTH translates this strategy into a likely urban morphology, it would be vital to know how (i) the forecasted growth will impact house prices, mobility patterns, redevelopment of the existing building stock, ecosystems' composition, urban microclimate and so on, and (ii) how this strategy can be efficiently achieved in the first place through investment, taxation, or other interventions, and what would these interventions mean for the welfare of households and firms. As such tasks are beyond the scope of SLEUTH, it should be stated that SLEUTH, with its rare ability to model urban growth in a spatially disaggregate manner, can serve as a link between various other models that focus on the behavior of multiple urban economic sectors (urban microeconomic models; integrated land use transport models; regional CGE models) but cannot distribute growth in a fine resolution grid as SLEUTH does.

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V

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Exploring the spatiotemporal behavior of Helsinki’s housing prices with fractal geometry and co-integration, *Journal of Geographical Systems* (accepted).

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Abstract: Fractal geometry and cointegration are combined for exploring spatial morphological aspects of quarterly dwelling prices in Helsinki's region from 1977 to 2011. Curves of fractal scaling behavior are first employed to measure the fractal dimensions of high and low price/m^2 spatial clusters at multiple scales. Subsequently, the fractal dimensions at indicative neighborhood and citywide scales are modeled with vector error correction specifications. The results identify long run joint equilibria between the fractal geometries of high and low price/m^2 clusters at both spatial scales. High price/m^2 clusters exhibit consistently higher fractal dimensions than their low value counterparts at the neighborhood scale, while this long run relation is reversed at the citywide scale. Short run disequilibria and subsequent adjustments are also scale sensitive. The fractal geometry of high price/m^2 clusters leads the dynamics at the neighborhood scale, while low price/m^2 clusters lead at the citywide scale. The system’s responses to exogenous shocks take longer time to stabilize at the neighborhood scale compared to the citywide scale, but in both scales the non-stationary nature of fractal behavior is evident. These elements indicate that a closer look on spatial economic behavior at more than one spatial and temporal scale at a time can reveal nontrivial information in the context of urban research and policy analysis.

Keywords: fractals; co-integration; residential property value; multiscale dynamics

JEL codes: R12; R31; C62; C63

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1 Introduction

The spatial variation of residential real estate value is widely used as an indicator in understanding the impacts of urban planning interventions (e.g., Perino et al. 2014; Votsis and Perrels 2016) and as an element in modeling the flows and interactions of an urban economy's spatial equilibrium (e.g., Wegener 1994; Anas 2013; Echenique et al. 2013). Moreover, differentiating between areas of high and low property prices is a typical step in understanding and modeling urban growth and land use (Brueckner et al. 1999; O'Sullivan 2000; Brueckner 2011).

Housing prices are formed and driven by multiple equilibria and by processes that operate at more than one spatial and temporal scales. Hedonic price theory (Rosen 1974; Dubin 1988; Sheppard 1999; DiPasquale and Wheaton 1996) and the Alonso-Muth-Mills (AMM) family of models (Alonso 1964; Mills 1967; Muth 1969) are microeconomic approaches that explain the formation and differentiation of residential property prices, but they also contain unaddressed issues with respect to spatial and temporal behavior. Firstly, each approach refers to processes that are particular to one spatial scale. The AMM approach is a citywide aggregate model that derives property prices from the location behavior of firms and households in relation to transport costs, distance to the city center, and the geographical configuration of amenities (Brueckner et al. 1999). In contrast, hedonic price theory refers to a buyer-seller matching process and decomposes realized market prices into implicit prices of a spatial vector of structural, locational, and neighborhood attributes of the properties themselves. An economic theory that approaches residential property prices across spatial scales is not available, although multiscale spatial economic analysis is a growing field (Batty 2007; Wegener 2008; Ioannides 2013). Secondly, although the AMM model implies that in the long run a stable spatial configuration of property prices is established—as part of a city's spatial equilibrium (see e.g., O'Sullivan 2000, Glaeser and Gottlieb 2009, Brueckner 2011)—short run volatility is a typical feature of housing prices as empirical time series and hedonic studies show. Elaborating on these short run dynamics and their relationship to the long run spatial equilibrium is particularly relevant for the time scales in which urban planning, decision-making, and several of the issues they aim to address are operating.

This paper aims to explore empirically multiple spatial and temporal scales together, by approaching the geographical behavior of housing prices as a time series. The study's focus is not on the underlying factors of housing price formation and differentiation and its adjustments; the interest is instead on the long and short run spatial characteristics of housing prices as realized in urban space at multiple spatial scales. The approach is inspired by time series macroeconometrics and may illuminate less-studied but important aspects of urban economic behavior. Two particular spatiotemporal aspects are of interest: the geographical behavior of housing prices at more than one spatial scale (i.e., a more elaborate view of space), and the interplay between long run equilibrium and short run out-of-equilibrium spatial processes (i.e., more details in temporal behavior).

Equilibrium can have multiple meanings, depending on the process being modeled. In this paper, the notion of equilibrium is empirical and relates to the long run spatial configuration of high and low property prices. Out-of-equilibrium behavior is understood here as quarterly volatilities and adjustments (of spatial configuration of housing prices) around the long run equilibrium. The concurrent look at equilibria and disequilibria is backed by research in agent-based economics (Filatova et al. 2009; Ettema 2011; Filatova and Bin 2013) and by time series studies of land value and property prices (Kenny 1999; Oikarinen 2005, 2014; Saarinen 2013). Moreover, the specifics of in- and out-of-equilibria processes are expected to vary at different spatial scales, as cities are increasingly shown to contain multiscale processes (Batty and Longley 1994; Batty 2007).

These aspects are explored using housing prices in the metropolitan region of Helsinki in the period between 1977 and 2011. The aim of analyzing multiscale spatial behavior motivates the use of fractal geometry and in particular the curves of fractal scaling behavior, which represent a non-Euclidean understanding of geographical space. The aim of studying the interplay between in- and out-of-equilibrium behavior motivates the use of the concept of co-integration and the estimation of vector error correction models. The co-integration analysis of the fractal behavior of property prices captures the volatile behavior of property prices in space and time as a process that underlies an overly stable spatial equilibrium at the micro and macro scales.

2 Methodology

Fractals are mathematical sets, the visualization of which produces complex shapes that are self-similar across scales of magnification (Mandelbrot 1967, 1982). In the case of spatial scales, a fractal entity fills space in a self-replicating manner, and this property of self-affinity has been utilized in urban studies to explore growth processes of the built environment and characterize its spatial morphology (Batty and Longley 1994; Batty 2007).

Various methods are available for estimating the fractal dimension. This study uses grid counting. Assume a binary image of a geographical object, with black pixels representing the object and white pixels otherwise. Let a square frame with edge length ε count the number of black pixels N that fall inside its perimeter, and repeat the procedure by increasing ε at specified intervals and recounting N. From the multiple counts of N at various increments of ε, we can estimate N as a function of ε and include an adjustment factor α (Frankhauser 1998; Thomas et al. 2008, 2012), so that:

$$N(\varepsilon) = \alpha\, \varepsilon^{D}. \tag{1}$$

D corresponds to the fractal dimension and ranges from zero to two. $D = 0$ indicates a mass concentrated at a single point, $D < 1$ is a scattered/disconnected pattern of clusters ('dust'), $D > 1$ is a connected pattern of clusters ('carpet') and $D = 2$ is a uniformly scattered mass.

It can be further assumed that fractal dimension D depends on scale ε (Thomas et al. 2010). This happens when the spatial morphology of an entity exhibits sharp changes from one scale to another, as in the transition from single buildings to building blocks, neighborhoods, and larger zones. Varying D with ε produces the curve of fractal scaling behavior (CFSB), which is a sequence of fractal dimensions that characterizes a sequence of scales, so that fractal behavior across a continuum of scales is simultaneously assessed. The CFSB has been used to identify critical scales at which fractal behavior (i.e., spatial morphology) changes significantly and as detailed signatures of particular types of urban morphologies (Batty 2001; Thomas et al. 2010). Frankhauser (1998) and Thomas et al. (2010) derive Eq. (2) from Eq. (1) that describes the CFSB

$$\frac{\mathrm{d}\log[N(\varepsilon)]}{\mathrm{d}\log(\varepsilon)} \equiv A(\varepsilon) = \frac{\mathrm{d}\log[\alpha(\varepsilon)]}{\mathrm{d}\log(\varepsilon)} + \frac{\mathrm{d}\,D(\varepsilon)}{\mathrm{d}\log(\varepsilon)}\log(\varepsilon) + D(\varepsilon). \tag{2}$$

The CFSB series can be volatile and if exhibiting non-stationarity, the concept of co-integration is particularly useful. This concept originates from time series econometrics and is frequently used in macroeconomic analysis. Its basic idea is the estimation of the relationship between at least two non-stationary time series over time t. Such series pose challenges to standard estimation methods. Often a variable that is non-stationary in its levels becomes stationary when considering its differences at times t and t-d, where d denotes temporal distance. Depending on the value of d that is needed to render the variable's differenced series stationary, the variable is referred to as integrated non-stationary of order d, or $I(d)$.

In certain cases, the linear combination of two or more non-stationary integrated variables produces a stationary time series. In particular, if variables x and y are integrated of order d, and a linear combination of them is integrated of order d-l, then x and y are co-integrated of order l. This suggests that although a number of variables can fluctuate (quasi)randomly over time, a linear combination of them can be stationary. The Granger-Engle representation theorem (Engle and Granger 1987) states that if x and y are co-integrated, they will have an error correction representation, where the error correction term is their co-integration relationship.

Johansen (1988, 1991, 1995) proposed to analyze the co-integrating relationship in a multi-equation setting by using a K-variable second order vector autoregressive (VAR) model, representing a class of multivariate, multi-equation autoregressive time series models. Johansen's approach uses a VAR model as the basis to estimate and interpret the endogenous dynamics between non-stationary series, and the resulting model is called the vector error correction (VEC) model. The model considers the levels, differences, and lags of a vector of co-integrated variables and estimates their stationary linear combination, referred to interchangeably as the co-integrating behavior, co-integrating relationship, or long run (joint) equilibrium relationship, and the more immediate volatile behavior around the equilibrium, referred to as the short run adjustment behavior. Additional vectors of trend parameters can be included to the short and long run relationships, producing the VEC equation given by

$$\Delta \boldsymbol{y}_t = \boldsymbol{\gamma} + \boldsymbol{\tau}\, t + \boldsymbol{\alpha}(\boldsymbol{\beta}'\mathbf{y}_{t-1} + \boldsymbol{\nu} + \boldsymbol{\rho}\, t) + \textstyle\sum_{i=1}^{p-1} \boldsymbol{\Gamma}_i\, \Delta \boldsymbol{y}_{t-i} + \boldsymbol{u}_t. \tag{3}$$

In Eq. (3), $\boldsymbol{y}_t$ is a $K \times 1$ vector of $I(1)$ co-integrated variables that have r co-integrating relationships in the range $0 < r < K$, Δ denotes first differences, $\boldsymbol{\gamma}$ and $\boldsymbol{\tau}$ are $K \times 1$ vectors of trend parameters, $\boldsymbol{\nu}$ and $\boldsymbol{\rho}$ are $r \times 1$ vectors of trend parameters, $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are $K \times r$ coefficient vectors, the prime symbol ($'$) denotes the transpose operator, p is the order of the underlying VAR model, $\boldsymbol{\Gamma}_i$ is the sum of the $K \times K$ coefficient matrices of the underlying p-order VAR, and $\boldsymbol{u}_t$ is a $K \times 1$ vector of i.i.d. disturbances with zero mean and covariance matrix $\boldsymbol{\Sigma}_u$.

The parameter estimate, $\widehat{\beta}$, of $K \times r$ vector $\boldsymbol{\beta}$ is the co-integrating relationship of the variables in $\boldsymbol{y}_t$ and provides information about their long run equilibrium relationship. For the case of the present study, the long run relationship of two co-integrated variables y_1 and y_2 with one co-integrating relationship yields a 2×1 vector $\boldsymbol{\beta}$. The parameter estimate $\widehat{\beta} = [1, \beta]$ provides the linear combination of the two variables, i.e., $y_1 + \beta\, y_2 = 0$, which is stationary and called the co-integrating equation (CE). The parameter estimate, $\widehat{\alpha}$, of $K \times r$ vector $\boldsymbol{\alpha}$ provides information about the short run behavior of the co-integrated system, estimating the speeds of adjustment to the joint equilibrium after periods of disequilibrium.

While the co-integrating equation represented by $\boldsymbol{\beta}$ and the adjustment coefficients represented by $\boldsymbol{\alpha}$ provide basic intuitions about system behavior, further interpretation of the dynamics of the system represented by Eq. (3) is facilitated by impulse response analysis. Impulse responses track the responses of a variable in vector $\boldsymbol{y}$ to impulses from another variable in $\boldsymbol{y}$, assuming that the impulse is caused by a shock that is exogenous to the modeled system. Eq. (3) is an autoregressive process and can be re-written in a moving average (MA) form, in which $\boldsymbol{y}_t$ is explained by a series of i temporally lagged disturbances $\boldsymbol{u}_t$ with $K \times J$ coefficient matrix $\boldsymbol{\Phi}_i$. The jk^{th} element of $\boldsymbol{\Phi}_i$, $\varphi_{kj,i}$, is the impulse response of the j^{th} variable of Eq. (3) to a unit shock in the k^{th} variable of Eq. (3) i time periods in the past (Lütkepohl 2005). A graph of $\varphi_{kj,i}$ as a function of i is called the impulse response function (Hamilton 1994). This formulation assumes that the responses of the system to shocks in one of its variables occur in an uncorrelated manner and holding everything else constant. As Lütkepohl and Krätzig (2004) note, it is more reasonable to assume that shocks do not occur in isolation when the elements of $\boldsymbol{u}_t$ in Eq. (3) are correlated, that is, when its covariance matrix $\boldsymbol{\Sigma}_u$ is not diagonal. To address this, i.e., to reflect the instantaneous nature of changes in the system of Eq. (3), orthogonal impulse responses are calculated as $\boldsymbol{\Theta}_i = \boldsymbol{\Phi}_i\boldsymbol{P}$, with $\boldsymbol{P}$ being a matrix of the Choleski decomposition of $\boldsymbol{\Sigma}_u$ so that $\boldsymbol{\Sigma}_u = \boldsymbol{PP}'$. As previously, the jk^{th} element of $\boldsymbol{\Theta}_i$, $\theta_{kj,i}$, is the orthogonal impulse response of the j^{th} variable of Eq. (3) to a unit shock in the k^{th} variable of Eq. (3) that occurred i time periods in the past, taking into account the instantaneous changes in variables across the system. A graph of $\theta_{kj,i}$ as a function of i is the orthogonalized impulse response function (OIRF) for a particular impulse-response pair of variables in $\boldsymbol{y}$.

The complete mathematical representation of impulse responses is extensive and can be found in Hamilton (1994, 318–323), Lütkepohl and Krätzig (2004, 165–171), and Lütkepohl (2005, 51–63). Further details about VEC and their underlying VAR models are found in Hamilton (1994), Lütkepohl and Krätzig (2004) and Lütkepohl (2005). It should be noted that the econometric framework of VEC models does not typically include exogenous variables. They rather focus on endogenous dynamics between non-stationary variables. It is important to note that the application of VEC models in this paper enables to focus on the endogenous relationship between the spatial morphological characteristics of price clusters over time and across spatial scales.

3 Assumptions

The first assumption made is that, although the AMM and hedonic price models are typically seen as static, their intuited geographical configuration of low and high housing prices in a city can be regarded as overly stable and referred to as an empirical long run equilibrium. As discussed in Section 1, this is in line with the practice of referring to the land use, firm and household location, land rent, and property price patterns of an urban area as a spatial equilibrium. The second assumption is that high and low price clusters do not exhibit a stable morphology when considering shorter time frames, but a variable one due to fluctuations in factors such as supply and demand, macroeconomic conditions, and shifts in market preferences and sentiments. In other words, short run adjustments do not only refer to market prices, but their spatial realization as well. The third assumption is that short run and long run behavior can be empirically modeled as co-dependent, and that the particular parameters of this relationship are sensitive to spatial scale.

As previously discussed, two non-stationary series can have a stationary linear combination, and this provides a framework for examining the in- and out-of-equilibrium spatial economic behavior in relation to each other. Allowing Eq. (2) to vary by time and price category yields

$$\left\{\frac{\mathrm{d}\log[N(\varepsilon)]}{\mathrm{d}\log(\varepsilon)}\right\}_{wt} \equiv A(\varepsilon)_{wt} = \left\{\frac{\mathrm{d}\log[\alpha(\varepsilon)]}{\mathrm{d}\log(\varepsilon)}\right\}_{wt} + \left\{\frac{\mathrm{d}\,D(\varepsilon)}{\mathrm{d}\log(\varepsilon)}\right\}_{wt} \log(\varepsilon) + D(\varepsilon)_{wt}, \quad (4)$$

with w denoting the type of spatial cluster {high value; low value} and t time. Assuming that Eq. (4) produces two co-integrated time series, and inserting $D(\varepsilon)_{wt}$ in Eq. (3) gives

$$\begin{bmatrix}\Delta D(\varepsilon)_{\text{high}}\\ \Delta D(\varepsilon)_{\text{low}}\end{bmatrix}_t = \boldsymbol{\gamma} + \boldsymbol{\tau}\,t + \boldsymbol{\alpha}\left(\boldsymbol{\beta}'\begin{bmatrix}D(\varepsilon)_{\text{high}}\\ D(\varepsilon)_{\text{low}}\end{bmatrix}_{t-1} + \boldsymbol{\nu} + \boldsymbol{\rho}\,t\right) + \sum_{i=1}^{p-1}\boldsymbol{\Gamma}_i\begin{bmatrix}\Delta D(\varepsilon)_{\text{high}}\\ \Delta D(\varepsilon)_{\text{low}}\end{bmatrix}_{t-i} + \boldsymbol{u}_t. \quad (5)$$

Eq. (5) enables the co-integration analysis of the fractal behavior of low and high price clusters.

4 Data, spatial aggregation, and cluster identification

The analysis uses a sample of approximately 300,000 housing transactions, which record the selling price of properties in the metropolitan region of Helsinki (Helsinki City and its adjoining suburban municipalities of Espoo and Vantaa). The transactions cover the period between 1977 and 2011 and are voluntarily collected by a consortium of Finnish real estate brokers and refined and maintained by VTT (Valtion Teknillinen Tutkimuslaitos) Technical Research Centre of Finland Ltd.

The selling prices were de-trended by adjusting for inflation with 2011 as the reference year and normalized to EUR thousand per square meter by dividing the selling price of each property by its floor space as indicated in its transaction record. The implication of price adjustment for the subsequent analysis is that the prices of each year are made comparable as they all refer to 2011 levels; high and low prices/m^2 as well as the derived spatial clusters have a common baseline. Per-square-meter price normalization clears interfering factors, notably the size and type of dwelling, from the comparison of prices across the study area.

The observations were spatially aggregated in a 100×100 m lattice. Exploratory spatial autocorrelation tests indicated that clusters of about 50 to 200 m return the strongest spatial autocorrelation in property prices, so that a 100 m cell can be taken as a homogenous area as far as property price is concerned. A quarterly temporal resolution was chosen to capture the temporal behavior of property prices in reasonable detail. This produced 135 lattices of transaction realizations in space, from 1977Q2 to 2011Q4. The starting time period of the analysis is 1977Q2, because 1977Q1 contains an insufficient amount of observations. The cells of each lattice were classified into statistically significant high and low price/m^2 clusters by employing the Getis-Ord Gi* statistic (Getis and Ord 1992; Ord and Getis 1995). The significance upon which the clusters were identified was adjusted for multiple testing and spatial dependence using the false discovery rate correction method (Caldas de Castro and Singer 2006). Cells found as hot spots at 90% significance or better were classified as high price/m^2 clusters, and cells identified as cold spots at the 90% or better significance level were classified as low price/m^2 clusters. The influence of aggregation and clustering choices in the estimated results is further discussed in Section 6.

Fig. 1 displays examples of the clusters for three indicative years. The top row shows all realized dwelling transactions and the middle and bottom rows depict high and low price/m^2 clusters. The images indicate that the produced high and low price/m^2 cells are consistent with the residential property price gradient as predicted in the spatial equilibrium of the AMM model and with empirical hedonic studies: high price clusters are observed near the city center and low price clusters in the urban periphery.

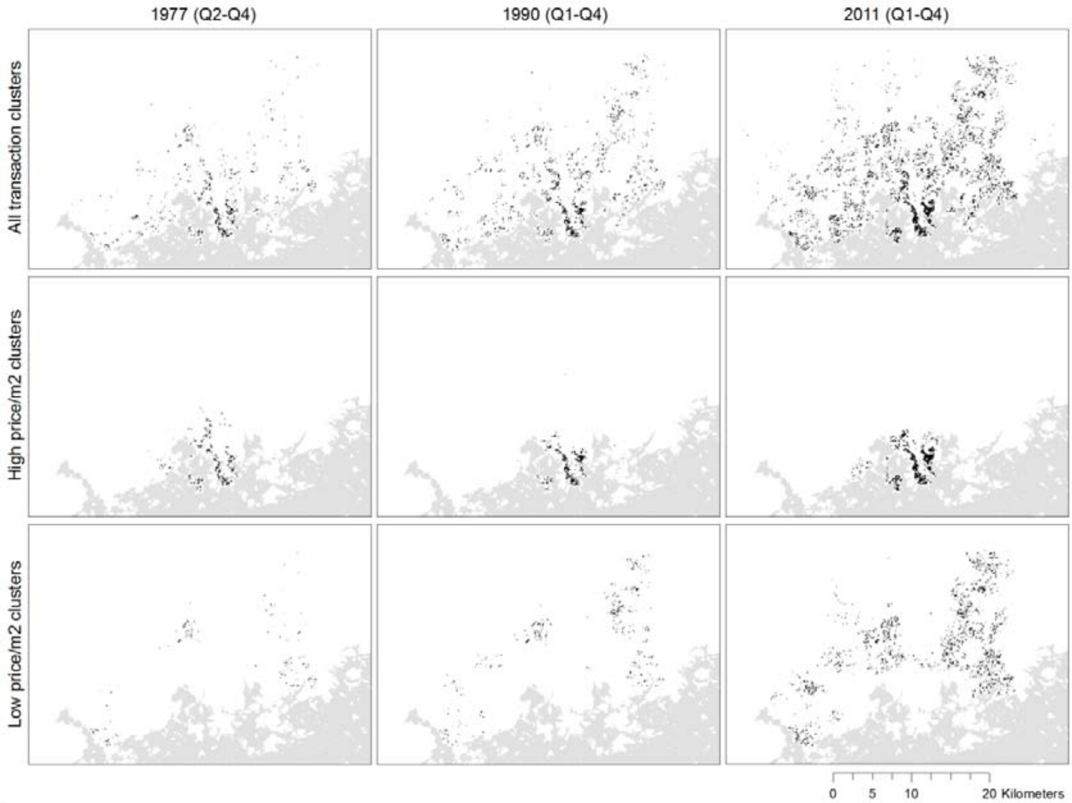

Fig. 1 Examples of the analyzed lattices

5 Results

This section firstly discusses the CFSB estimated for high and low price/m^2 clusters. The results of the co-integration analysis of the quarterly time series of fractal dimensions at the spatial scales of 200 m and 12,800 m are discussed afterwards. The section concludes by summarizing the results and discussing their main implications.

5.1 The estimated curves of fractal scaling behavior

The algorithms used to estimate Eq. (4) were provided by the tool 'Fractalyse' (*City, mobility, territory* research group at ThéMA, Université de Franche-Comté and Université de Bourgogne), and the clusters of high and low price/m^2 were calculated in ESRI ArcMap. Fig. 2 displays the decadal progression in the scaling behavior of high and low price/m^2 clusters.

The curves indicate that the fractal dimensions of the spatial clusters of both price categories have steadily increased between years 1977 and 2011 at the scales of 100 to 6,400 m, while the reverse is observed at the scale of 12,800 m, notably in the high price category. In the low price/m^2 category, the gradual increase in fractal dimensions is concurrent with a flattening of the scaling curve, which translates to the gradual elimination of sharp changes in cluster morphology across scales, especially at 6,400 m. The scaling behavior in the high price/m^2 category exhibits a similar smoothening between years 1977 and 1999, but sharp changes at 6,400 m re-emerge after year 2000. An additional point of notice is that in both price/m^2 categories, the scale of 6,400 m exhibits a gradual transition from fractal dimensions below one to dimensions over one, which is the limit of disconnected/connected morphology. Overall, the critical character of scales 800 m (or 800 m - 1,600 m) and 6,400 m is largely preserved throughout the four-decade period.

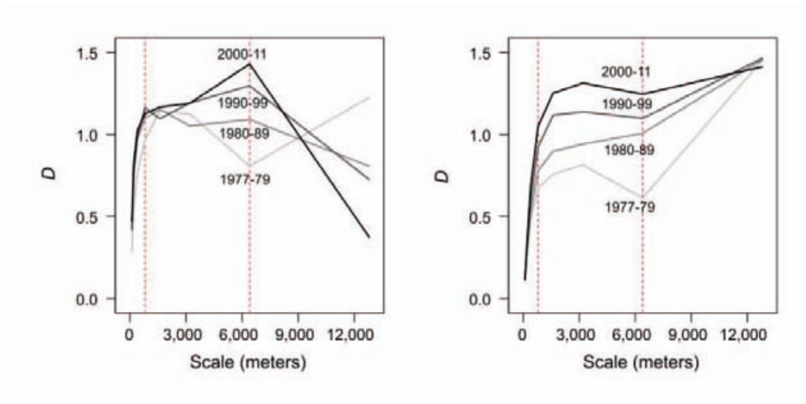

Fig. 2 Scaling behavior at decadal intervals of high (left) and low (right) price/m^2 clusters

The temporal behavior of the fractal dimensions of individual scales is clearer when the horizontal axis is used to represent time measured in quarters rather than distance (see Fig. 3). This lets the various curves at the same graph represent time series of fractal dimensions for each spatial scale.

It is possible to group the fractal evolution of different spatial scales into three sets: (a) micro scale behavior measured at the spatial scales of 100 m, 200 m, and 400 m; (b) meso scale behavior measured at the spatial scales of 800 m, 1,600 m, and 3,200 m; and (c) macro scale behavior at 6,400 and 12,800 m. This distinction echoes the critical scales of 800 m and 6,400 m discussed previously, and the main distinguishing factors are short run temporal volatility and the long run difference between the fractal dimensions of low and high price/m^2 categories. As scales progress from the micro towards the macro level, one can observe an increase in the volatility of the time series and a concurrent change in the relative magnitude of the fractal dimensions of the two price/m^2 categories. The volatility in the high price category is remarkable at the macro scales, with fractal dimensions registering across most of the spectrum of possible values (0–1.5 or 0.5–2). Curves in various scales exhibit obvious alternations between dimensions less than one and over than one. Long run equilibria around which the quarterly volatility takes place is also evident at all scales. A formal methodology for grouping and comparing curves of fractal scaling behavior has been proposed by Thomas et al. (2010), but has not been employed here, as the intuitions gained from Fig. 3 provide sufficient exploratory capacity in preparation of formal analysis with vector error correction models.

The CFSB encourages the idea that a separation of spatial scales will reveal non-trivial information, since there are critical transitions in spatial behavior when moving from the micro-scale towards the macro scale. Furthermore, the temporal structure in the fractal dimensions appears to depend on both scale and price cluster. The following section formally explores these assertions by estimating vector error correction models at micro and macro spatial scales.

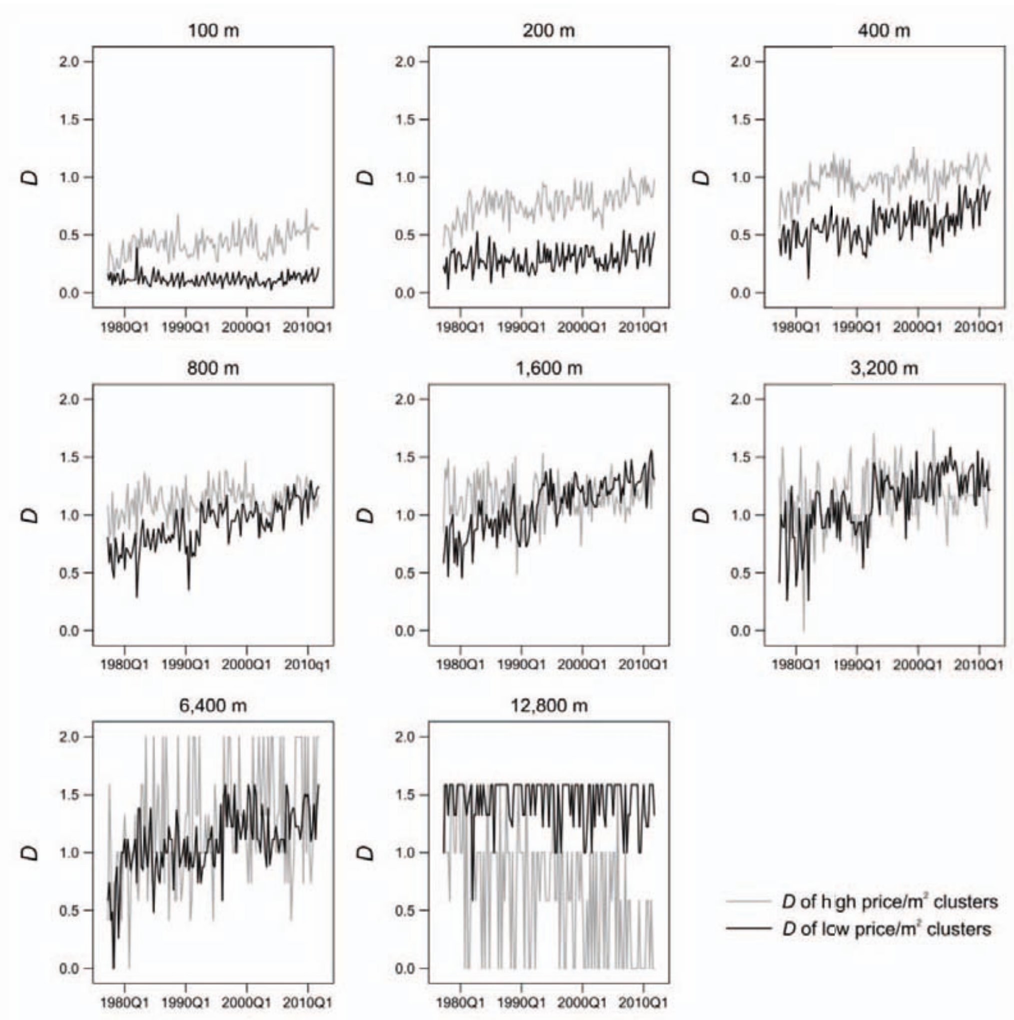

Fig. 3 Time series of the fractal dimension (D) of high and low price/m^2 clusters at eight spatial scales

5.2 Co-integration analysis

The intuition behind applying co-integration analysis to fractal dimension time series is that the fractal dimensions of high and low value clusters, in addition to their characteristics as individual time series, are engaged in a joint long run equilibrium relationship. Deviations due to the short run volatility of high and low value clusters do not last indefinitely. The morphologies of each price category adjust to recover the long run equilibrium. As explained in Section 2, the joint equilibrium is an empirical concept that helps to understand how one variable responds to fluctuations of its co-integrated pair.

The fractal dimensions of high and low value clusters at $\varepsilon = 200$ m and $\varepsilon = 12{,}800$ m (see Fig. 4) were selected as representatives for the micro scale and macro scale, respectively. The former corresponds to a neighborhood of a few building blocks and the latter is approximately 1.5 the radius of the urban area, with six sub-regions covering most of the area. Fig. 5 illustrates the two scales. The analysis was conducted in STATA 13.1. The hypothesis of a unit root in the level variables cannot be rejected by the augmented Dickey-Fuller (ADF) and modified Dickey-Fuller with generalized least squares (DF-GLS) *t*-tests, whereas it can be rejected for their first differences at the 99% confidence interval. The inference is that the fractal dimensions at both scales are non-stationary integrated $I(1)$ series, i.e., that while the variables themselves are non-stationary, their first differences are stationary.

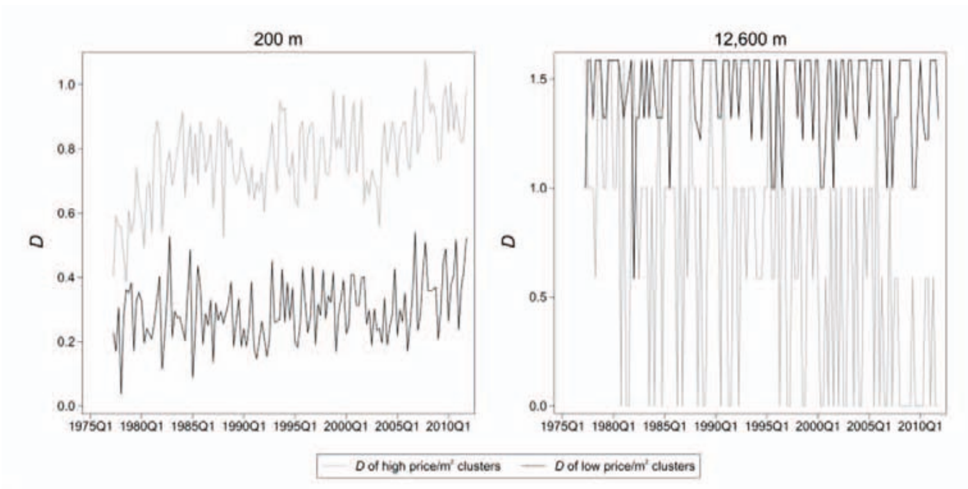

Fig. 4 Fractal time series at the spatial scales of 200 m (left) and 12,800 m (right)

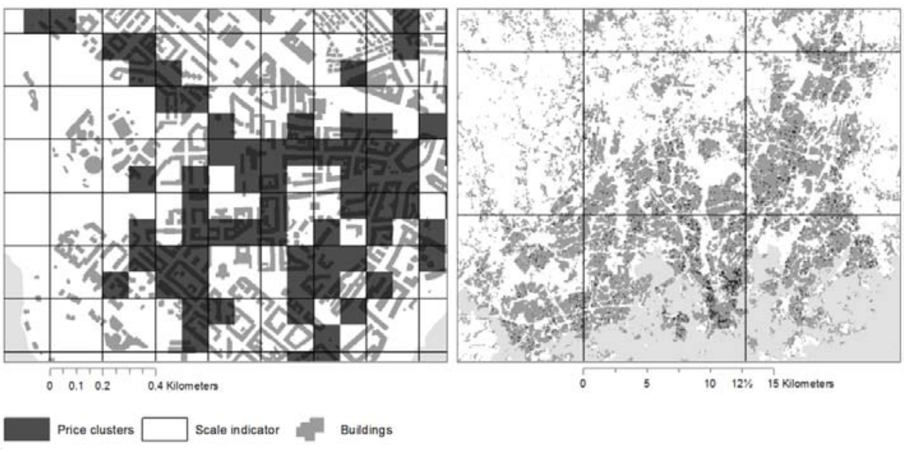

Fig. 5 The analyzed price/m^2 clusters at the scales of 200 m (left) and 12,800 m (right)

Since each individual fractal time series is non-stationary first order integrated, pairs of them at each spatial scale can be tested for co-integration. Eq. (5) was fitted to the fractal dimensions of high and low price clusters at scales ε = 200 m and 12,800 m. Information criteria searched for a plausible lag order p—indicating four lags for the models at both scales—and for confirming the logical expectation of one co-integrating relationship per two variables at each scale. It was decided to restrict the trend vectors $\boldsymbol{\gamma}$, $\boldsymbol{\tau}$, $\boldsymbol{v}$ and $\boldsymbol{\rho}$ of Eq. (5) to zero, assuming that this exclusion of trends will not misrepresent the modeled dynamics. This assumption was verified by post-estimation tests. Drawing from the assumption of residential location models that high bidders initiate the process of residential location sorting, the variable order was set to high value cluster followed by low value cluster at each scale. Table 1 summarizes the main components of the estimation process.

Table 1 Estimated VEC parameters

	(a) Micro scale (ε = 200 m)	*(c) Macro scale (ε = 12,800 m)*
Number of lags (p)	$p = 4$	$p = 4$
Trend assumptions	$\boldsymbol{\tau} = \boldsymbol{\rho} = \boldsymbol{\gamma} = \boldsymbol{v} = 0$	$\boldsymbol{\tau} = \boldsymbol{\rho} = \boldsymbol{\gamma} = \boldsymbol{v} = 0$
Time frame	1977Q2–2011Q4	1977Q2–2011Q4
No. of obs.	139	139
Co-integrating parameter vector ($\hat{\beta}$)	[1, –2.578]	[1, –0.441]
(p-value)	*(n/a, 0.000)*	*(n/a, 0.000)*
Adjustment speeds ($\hat{\alpha}$)	[–0.079, 0.263]	[–0.565, 0.003]
(p-value)	*(0.378, 0.000)*	*(0.000, 0.960)*

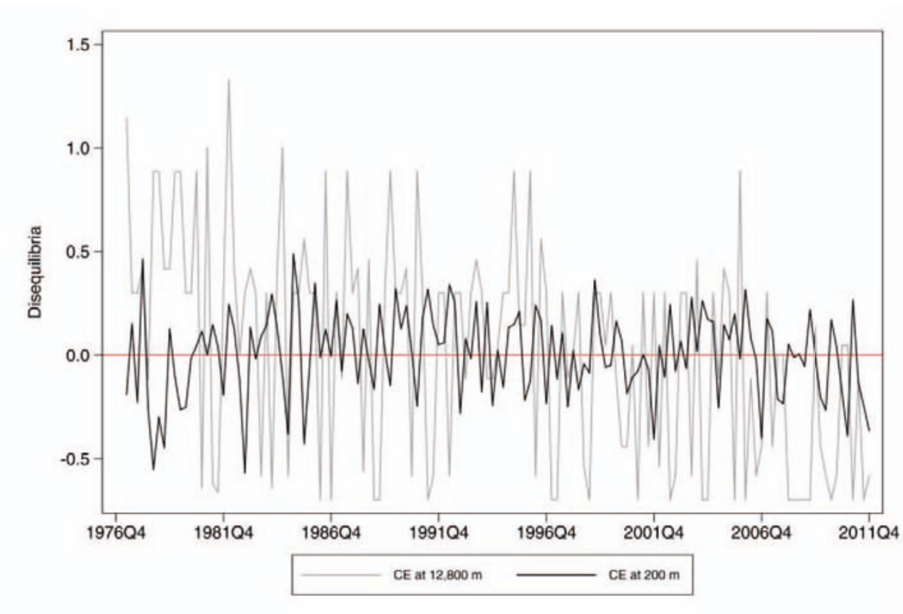

Fig. 6 Estimated co-integrating equations (CE), representing deviations from the joint equilibrium at the spatial scales of 200 m and 12,800 m

Deviations from the joint equilibrium of each scale can be traced in the corresponding co-integrating equation (CE) (see Fig. 6). The CEs show that, during the four decades under investigation, deviations from the equilibrium morphologies have been largely contained within +/– 0.5 fractal units at the scale of 200 m and within –0.7 and +0.9 at 12,800 m.

The information criteria for the model at ε = 200 m supported a fourth order VEC model (four lags) with one co-integrating relationship for the assumed restrictions $\boldsymbol{\tau} = \boldsymbol{\rho} = \boldsymbol{\gamma} = \boldsymbol{\nu} = 0$. The parameter estimate, $\hat{\beta}$, of the long run equilibrium relationship is given as [1, –2.578] and is highly significant. The parameter estimate, $\hat{\alpha}$, of the adjustment coefficients is [–0.079, 0.263] and only that of low value clusters is significant, while the adjustment of high value clusters is insignificant. The parameter estimate of β indicates that the long run equilibrium at the micro scale is characterized by a high value to low value cluster ratio of 2.6 in terms of their fractal dimensions, as also indicated by Fig. 4 (left), which translates to a consistently higher fractal dimension of high value clusters compared to that of low value clusters. In disequilibrium periods, the statistically insignificant adjustment coefficient of high value clusters suggests that when the fractal dimension of high value clusters deviates from its equilibrium, it does not tend to adjust back. This indicates a lead role for high value clusters in the overall dynamics. At the same time, low value clusters will tend to adjust in order to restore the joint equilibrium shown in the co-integrating equation at 200 m in Fig. 6. In these disequilibrium situations, the co-integrating equation implied by $\hat{\beta}$ shows that a one-unit change in the fractal dimension of high value clusters will lead to an approximately 0.39-unit change in that of low value clusters. Concerning the role of temporal lags, the fractal dimension of high price clusters is significantly influenced by its own values in past quarters but not by the past values of low price clusters, while the fractal dimension of low price clusters is influenced by the past values of both high and low price clusters. This reaffirms the indication that high price clusters lead the dynamics at the micro scale.

The orthogonal impulse responses explore the impact of a one-time shock of a variable in a co-integrated system on the other variables of the system and on itself (see Section 2). Fig. 7 presents the orthogonalized impulse response functions (OIRFs) for the estimated VEC model at the spatial scale of 200 m. There is a clear self-reinforcing feedback in high value clusters, i.e., a recursive additive response of the fractal dimension of high value clusters to its own change. Shocks in the fractal dimension of high value clusters induce an immediate positive response of about 0.1 fractal units and this reinforcing stabilizes to about 0.04 after 20 quarters (Fig. 7a). The response of low value clusters to impulses from high value clusters is also positive, starting at about 0.03 fractal units and stabilizing to about 0.02 units after 20 quarters (Fig. 7b). On the other hand, the self-reinforcing feedback in low value clusters is subdued relative to the corresponding feedback in their high value counterparts, with the effects stabilizing at about 0.01 fractal units after 20 quarters (Fig. 7c). The response of high value clusters to impulses from low value clusters starts at about 0.075 fractal units and fades to zero after 20 quarters (Fig. 7d). Overall, the OIRFs of Fig. 7 suggest that high value clusters drive the system at the spatial scale of 200 m. Exogenous shocks in the fractal dimension of high value clusters induce greater and permanent impacts across the system, while low value clusters have subdued, near-transient or transient effects. This is in line with the lead role of high value clusters that is discerned from the estimates of the adjustment coefficients α. Weak occasional negative impulse responses during the first quarters following an exogenous shock are also present (Fig. 7b-d), but are questionable due to the unavailability of standard error estimates.

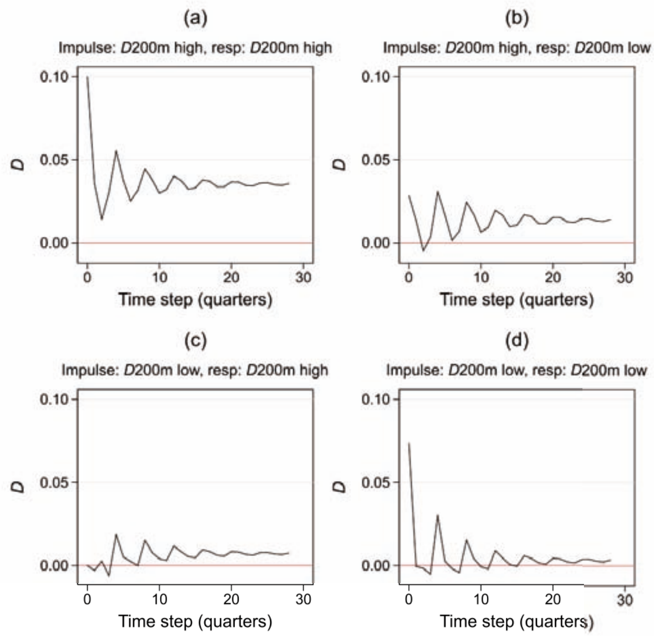

Fig. 7 Orthogonal impulse responses at micro scale ε = 200 m: (a) response of high value *D* to impulse of high value *D*, (b) response of low value *D* to impulse of high value *D*, (c) response of high value *D* to impulse of low value *D*, and (d) response of low value *D* to impulse of low value *D*

The model at ε = 12,800 m was fitted as a fourth order VEC model with the restrictions $\boldsymbol{\tau} = \boldsymbol{\rho} = \boldsymbol{\gamma} = \boldsymbol{\nu} = 0$. The tests support the expected number of one co-integrating relationship. The estimations returned a highly significant parameter vector $\hat{\beta}$ = [1, –0.441] for the long run relationship. The estimates of the adjustment coefficients, $\hat{\alpha}$, are given by [–0.565, 0.003] with only the adjustment of high value clusters being significant. These results suggest that the long run equilibrium is characterized by a high to low value cluster ratio of 0.4 in terms of their fractal dimensions. This indicates that, as a rule, high value clusters exhibit a consistently lower fractal dimension than their low value counterparts (see also Fig. 4 right). This is a reversal of the results at the micro scale. In periods when the fractal dimension of low value clusters is above or below its equilibrium, it will not tend to adjust. During these periods, high value clusters will tend to adjust in order to restore the joint equilibrium shown in the co-integration equation at 12,800 m of Fig. 6. These elements indicate a lead role for low value clusters in the citywide dynamics. The parameter estimate of $\boldsymbol{\beta}$ shows that during disequilibria, a one-unit change in the fractal dimension of low values will induce an approximately 0.44-unit change in the fractal dimension of high value clusters. Compared to the scale of 200 m (0.39) this is a slightly higher 'elasticity'. Concerning the role of temporal lags, the fractal dimension of high price clusters is significantly influenced by its own values in past quarters and by the most recent quarter of low price clusters, while the fractal dimension of low price clusters is only influenced by its past quarters. This supports the idea that low price clusters are the leads in the dynamics of this scale.

The suggested lead role for low value clusters at the citywide scale is the reverse of what is found at the neighborhood scale, but potentially conflicts with the assumed variable order. To further check this, a VEC model with the alternate variable order (fractal dimension of low value clusters followed by that of high value clusters) was estimated and indicated the same dynamics. The estimations returned a highly significant parameter estimate, $\hat{\beta} = [1, -2.270]$, outlining an identical long run relationship as above (the inverse coefficients since the order of variables is swapped), an insignificant adjustment coefficient for low value clusters, and a highly significant adjustment coefficient for high value clusters.

The OIRFs presented in Fig. 8 indicate that the macro scale dynamics are driven chiefly by shocks in the fractal dimension of low price clusters. Changes in the fractal dimension of low value clusters appear to induce permanent effects in the system, while their high value counterparts induce near transient effects. These elements indicate a reversal from the micro scale. In particular, the self-reinforcing feedback in low value clusters starts at 0.2 fractal units and stabilizes to 0.1 after ten quarters (Fig. 8d), while the response of high value clusters to impulses from low value clusters, exempting initial oscillations, is relatively stable at 0.05 units after eight quarters (Fig. 8c). The self-reinforcing feedback in high value clusters starts rather strongly at 0.5 fractal units, but drops rapidly in the next quarters, reaching to zero after about ten quarters (Fig. 8a). The response of low value clusters to impulses from high value clusters starts at 0.1 units and stabilizes to near zero after eight quarters (Fig. 8b). As with the model at the micro scale, the indications of negative impulse responses are rather weak.

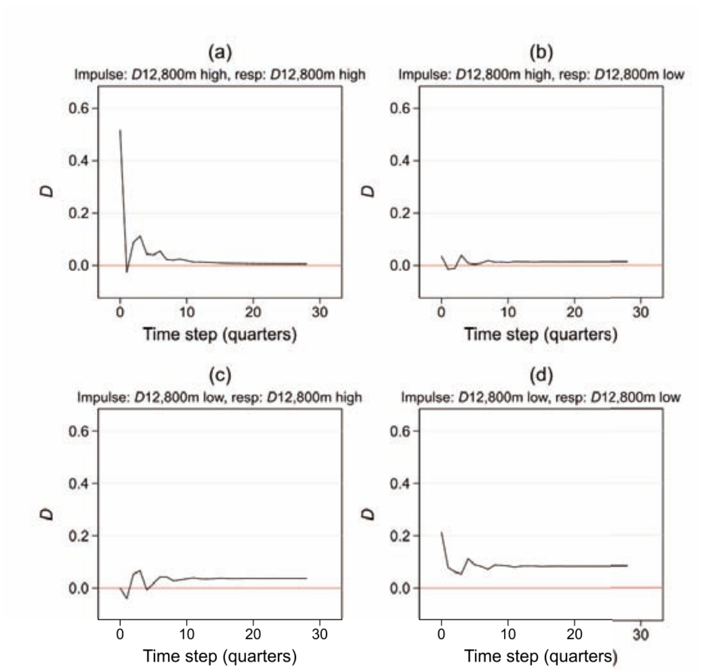

Fig. 8 Orthogonal impulse responses at macro scale $\varepsilon = 12{,}800$ m: (a) response of high value D to impulse of high value D, (b) response of low value D to impulse of high value D, (c) response of high value D to impulse of low value D, and (d) response of low value D to impulse of low value D

It was discussed earlier that the lead role in the dynamics of the neighborhood (micro) scale is assigned to the fractal dimension of high value clusters. This result is in line with the assumption of residential location models that the sorting process is initiated by the bids of wealthy households for high amenity areas and thus establishing high land value areas, followed by a filling-in of lower land values in the remaining locations. Furthermore, this agreement in the lead dynamics is found at the correct spatial scale, since the neighborhood or micro scale is typically associated with microeconomic behavior at relatively refined spatial scales. Conversely, the lead role in the dynamics of the citywide (macro) scale was assigned to the low value clusters. Recalling that this is a coarse scale, the property value morphology will resemble a smooth bid-rent gradient with low value clusters located at the urban periphery. The results thus suggest that dynamics are led by the low value clusters at the periphery, with high value clusters having to adjust to deviations from the equilibrium. This is interestingly consistent with Oikarinen (2005), who reports that prices in the periphery of Helsinki's metropolitan region diffuse towards—or Granger-cause—prices in the center. Lastly, the fact that the leads in each spatial scale tend to not adjust when they enter a state of disequilibrium, but will rather cause their counterparts to adjust, is characteristic of the non-stationary character of the system, and is in line with the gradual growth in fractal dimensions that was discussed in the previous section.

5.3 Summary of the results

Curves of fractal scaling behavior were estimated for spatial clusters of high and low residential property prices. These curves track the quarterly variation in the spatial morphology of high and low price/m^2 areas across Helsinki's metropolitan region from the second quarter of 1977 to the fourth quarter of 2011. The time series of fractal dimensions at indicative neighborhood ('micro') and citywide ('macro') scales were modeled with vector error correction specifications, exploring long run and short run joint behavior in the spatial morphologies of high and low price clusters.

Based on the results, summarized in Table 2, a number of points can be made. The point of departure is that the temporal behavior of housing prices is a concept that does not only relate to price levels, but also to their spatial morphology. Although this analysis does not provide information about the functional relationship between the two quantities, it nevertheless suggests that a policy discussion interested in short run and long run price behavior can revolve not only around the fluctuation of prices and their potential impacts, but also about the implications of fluctuations in the morphological characteristics of price clusters in urban space (the fractal geometry of which is just one aspect).

The co-integration analysis indicates that equilibrium-disequilibrium relationships between the quarterly morphologies of high and low price/m^2 clusters are present across spatial scales, but with differing specifics at each scale. At the micro (neighborhood) scale, high price/m^2 clusters are, in the long run, of consistently higher fractal dimension compared to low price/m^2 clusters, while this relation is reversed at the macro (citywide) scale. Short run adjustments following periods of disequilibria are also scale sensitive. The fractal behavior of high price/m^2 clusters leads the dynamics at the neighborhood scale, while low price/m^2 clusters lead at the citywide scale. The system's responses to exogenous shocks take about twice the time to stabilize at the neighborhood scale (20 quarters) compared to the citywide scale (eight to ten quarters).

Table 2 Summary of the results (D denotes fractal dimension)

	Neighborhood scale (200 m)	Citywide scale (12,800 m)
Fractal geometry	$D \approx 0.7$ for high price/m^{2}clusters and ≈ 0.2 for low price/m^2 clusters. Quarterly volatility $\approx$ +/– 0.2 in both price/m^2 categories; $I(1)$ non-stationary series.	$D \approx 0.5$ for high price/m^2 clusters and ≈ 1.3 for low price/m^2 clusters. Quarterly volatility $\approx$ +/– 1 for high price/m^2 clusters and $\approx$ +/– 0.3 for low price/m^2 clusters; $I(1)$ non-stationary series.
Long run equilibrium	D of high price/m^2 clusters is approx. three times that of low price/m^2 clusters.	D of high price/m^2 clusters is approx. 0.4 times that of low price/m^2 clusters.
Short run adjustments	Led by high price/m^2 clusters. Low price/m^2 clusters adjust to short run fluctuations of high price/m^2 clusters to restore joint equilibrium. High price/m^2 clusters do not adjust.	Led by low price/m^2 clusters. High price/m^2 clusters adjust to short run fluctuations of low price/m^2 clusters to restore joint equilibrium. Low price/m^2 clusters do not adjust.
Orthogonal impulse responses	High price/m^2 clusters have permanent effects. Low price/m^2 clusters have near transient effects. Effects stabilize in 20 quarters.	High price/m^2 clusters have transient effects. Low price/m^2 clusters have permanent effects. Effects stabilize in eight to ten quarters.

The aforementioned aspects of the spatial economy are consistent with urban complexity's notion of synchronous multiscale processes in cities (Batty and Longley 1994; Batty 2007) and suggests that considering spatial economic behavior at more than one spatial and temporal scale at a time can reveal nontrivial information. At a more abstract level, it is also evident that the 'edge of chaos' notion (Packard 1988; Langton 1990; Farmer, cited in Waldrop 1994 and McMillan 2004) is relevant in urban economics since co-integration analysis can be regarded as one way to explore the temporal balance between chaotic and ordered conditions in key variables such as the spatial arrangement of residential real estate prices. These bring attention to the question of how the estimated equilibrium-disequilibrium relationships and their sensitivity to spatial scale relate to the processes described in the Alonso-Muth-Mills model and hedonic price theory. A first question would be whether certain spatial scales can be associated with the process of a particular model. A second question would be how the long run and short run relationship of high and low price/m^2 clusters relates to particular states, if any, of the two approaches.

Next, the findings support the idea that the typical view of cities as homogeneous areas of agglomeration benefits that decline with distance to the city center—or to amenity- or service-rich nodes of a multicentric system—should be perhaps revisited when spatially detailed policy analysis is of interest. The results suggest that, as far as residential property value is concerned, the benefits are in practice characterized by (a) a particularly granular morphology, which (b) differs across spatial aggregation scales, and (c) contains high and low price/m^2 agglomerations that are more complex than a multicentric view of cities and pulsate, drift, and change their spatial morphology in a highly volatile manner, although in the long run they can be regarded as stable.

Lastly, the results justify that increasing the level of spatial (i.e., more than one scale) and temporal (i.e., the relationship between long run and short run behavior) detail is important, as a large set of contemporary urban issues—ranging from smart, green cities through to climate-resilient and comprehensibly sustainable cities—involves impacts and autonomous or planned responses that involve a mix of phenomena at more than one spatial and temporal scale. Increasing the understanding of how price effects can be distributed in urban space in different ways depending on scale and price level is important for precise and effective decision making.

6 Closing remarks

A few points of attention should be noted concerning the interpretation of the modeled dynamics.

Firstly, the choice of aggregating the price observations into a 100 m square lattice, i.e., a choice of a certain shape to represent price clusters, has an influence on the measured fractal dimensions. An alternative option would be to use disaggregate point observations, but this does not offer clear advantages. On one hand, points are not represented in raster images as dimensionless entities but are drawn, too, as pixels of certain size and shape. Thus, the generated raster image, from which fractal dimensions are measured, will also contain assumptions about the shape and size of price clusters. If the objective is to represent price/m^2 points in as much a detailed manner as possible, then analyzing the physical footprint of properties would be logical, but the analysis would then relate to the morphology of the built environment and not to price clusters. On the other hand, the lattice offers a standardized measure of the way price/m^2 fills and varies across the urban area. Housing transactions are known to exhibit spatial autocorrelation (Dubin 1988), which means that the housing market behaves reasonably homogeneously inside an area of a certain size; the chosen aggregation preserves a sufficiently high spatial autocorrelation degree in the analyzed price variable while clearing the data from the difficult-to-interpret (for studies of large urban areas) and not free of errors variation of completely disaggregate observations. The standardized and homogeneous nature of an aggregated but very fine-resolution lattice and the fact that point observations are not trouble- or assumption-free meant that the chosen option, combined with a quarterly time step, represents an analytical setup better fitted for studying the spatial and temporal behavior of housing prices.

Next to the choice of cluster shape, the methodology of identifying clusters of high and low house prices also potentially influences the derived clusters. To check this, the analysis was repeated with a different cluster identification methodology (LISA clusters – Anselin 1995), different shape (hexagonal cells sized at approximately 150 m) and by measuring total price rather than per m^2 normalized price. The identified clusters differ only slightly between the Gi* and LISA methodologies and the results in this counterfactual case are largely the same. A second aspect is the comparison of clusters between quarters and the validity of probability thresholds used to identify the clusters of each separate quarter. This has been addressed first by adjusting the price levels to a common baseline, therefore making the high and low price/m^2 clusters in every quarter to refer to the same baseline level (i.e., the cluster algorithm is applied in multiple instances of a large ‘cross-section’) and second by employing the false discovery rate methodology (Caldas de Castro and Singer 2006) as a guard against misidentified clusters. While other methodologies might be applied to check the robustness of identified clusters, the abovementioned counterfactual tests suggest that the identified dynamics are not detrimentally sensitive to the choice of cluster identification methodology, as long as the prices are adjusted to a common baseline and the size of aggregation lattice matches the spatial scale at which the housing transactions operate.

Secondly, as each quarter contains transactions for both old and new properties, two main spatial processes are assumed to be mixed in the presented results: the growth of the housing stock; and spatial morphological fluctuations due to internal price adjustments of the existing stock. A first procedure to explore this issue would be to separate the fractal time series in trend and cyclical components. In this case, the trend would contain the gradual growth of fractal dimensions, associated with the growth of the housing stock. Conversely, the cyclical components would contain the influence of economic cycles and of internal adjustments. A second procedure would be to use cumulative patterns by stacking each quarter upon the previous ones. Although this is typical in urban morphology studies, it would overemphasize the trend (growth) component of the fractal dimensions and eliminate the information represented by the quarterly volatility. A third procedure would be to remove the transactions of new dwellings from each quarter. This, however, conflicts with the basic idea that new and old dwellings are both part of the search and bid process and both influence the formed prices in the housing market in each quarter.

The issue relates in fact to what part of the VEC equation refers to the modification of fractal geometry due to the physical expansion and densification of the housing stock, and what part refers to the adjustments of the fractal geometry of housing price clusters. By extension, it also relates to the relation of the trend and cyclical components to the idea of a joint equilibrium and short run adjustments in the spatial morphology of price/m^2 clusters. Trend and cycles typically relate to single time series, while VEC models focus on joint relationships. An assumption would be that trend terms in the long run equilibrium relationship (not included here) reflect the gradual growth of the housing stock, while the adjustment coefficients might relate to the internal adjustments of the housing stock and the influence of economic cycles. On the other hand, the non-stationarity of the co-integrated systems also reflects growth behavior. Additionally, the interpretation of trend terms in the levels and/or differences of the fractal dimensions would also need to be explored, but in this empirical sample the inclusion of such terms was not supported by specification tests. To address these issues, a study connecting the variation in the levels of prices with the variation in the spatial morphology of prices would be necessary, which would be an interesting extension of this study.

Thirdly, the analyzed housing prices are a sample of total transactions each year. This introduces biases in the analyzed spatial morphologies. It is alleviated by the fact that the inputs of the largest real estate brokers of Helsinki's metropolitan region are included in the sample, but the fact that the dataset does not capture the entire housing market is an important limitation. Furthermore, the rate of participation in this voluntary data reporting program may have annual variations, especially when the time frame of the analysis extends back to 1977, when participation was scarcer. Nevertheless, it is likely that this analysis does not suffer significantly from such biases, since the employed grid of average price/m^2 cells is a first measure to alleviate this problem, the 1997Q2 was specifically selected as the starting point as the number of observations becomes sufficient from that point in time, and the produced time series of spatial clusters does follow the factual urban development in Helsinki.

Fourthly, further examinations might consider the inclusion of exogenous variables, which is especially important for policy analysis. VEC models are specialized in the endogenous dynamics between non-stationary variables, but they are still VAR models at their core. VAR models are better geared in modeling exogenous effects in time series. A joint use of VAR and VEC models can therefore be recommended as a strategy for addressing both exogenous and endogenous effects.

Lastly, cross-scale characteristics need to be explored in more detail. Preliminary modeling of the fractal dynamics simultaneously at all spatial scales and with exogenous parameters has indicated notable cross-scale diffusions of endogenous and exogenous effects and Granger-causalities. A reasonable extension of this study would be to consider a single VEC model that includes dynamics of multiple spatial scales. This would encourage the use of more advanced aspects of VEC modeling. Similarly, there are strong indications that the identified price clusters are multifractal, that is, composites of multiple sub-morphologies. A multifractal analysis framework would thus be beneficial. Ultimately, it would be of interest to associate the estimated fractals to mathematical ones. This would allow the drafting of a reference typology and the analytical modeling of the dynamics that have been examined here only numerically.

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